An introduction to electronics

Contents

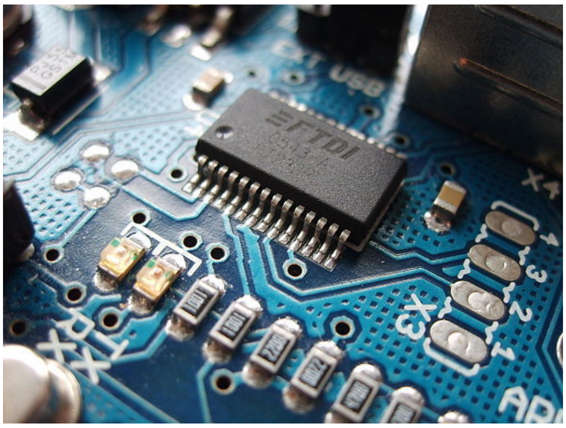
Chapter 1

Introduction

1.1 Electronics

This article is about the technical field of electronics. For personal-use electronic devices, see consumer electronics. For the scientific magazine, see Electronics (magazine).

Electronics is the science of how to control electric



Surface-mount electronic components

energy, energy in which the electrons have a fundamental role. Electronics deals with electrical circuits that involve active electrical components such as vacuum tubes, transistors, diodes and integrated circuits, and associated passive electrical components and interconnection technologies. Commonly, electronic devices contain circuitry consisting primarily or exclusively of active semiconductors supplemented with passive elements; such a circuit is described as an electronic circuit.

The nonlinear behaviour of active components and their ability to control electron flows makes amplification of weak signals possible, and electronics is widely used in information processing, telecommunication, and signal processing. The ability of electronic devices to act as switches makes digital information processing possible. Interconnection technologies such as circuit boards, electronics packaging technology, and other varied forms of communication infrastructure complete circuit functionality and transform the mixed components into a regular working system.

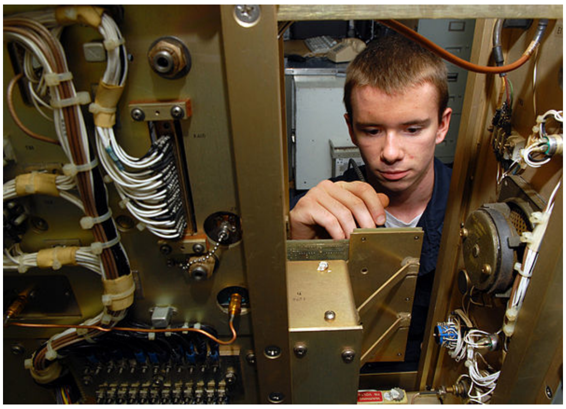
Electronics is distinct from electrical and electro-mechanical science and technology, which deal with the generation, distribution, switching, storage, and conversion of electrical energy to and from other energy forms using wires, motors, generators, batteries, switches, relays, transformers, resistors, and other passive components. This distinction started around 1906 with the invention by Lee De Forest of the triode, which made electrical amplification of weak radio signals and audio signals possible with a non-mechanical device. Until 1950 this field was called “radio technology” because its principal application was the design and theory of radio transmitters, receivers, and vacuum tubes.

Today, most electronic devices use semiconductor components to perform electron control. The study of semiconductor devices and related technology is considered a branch of solid-state physics, whereas the design and construction of electronic circuits to solve practical problems come under electronics engineering. This article focuses on engineering aspects of electronics.

1.1.1 Branches of electronics

Electronics has branches as follows:

1. Digital electronics
2. Analogue electronics
3. Microelectronics
4. Circuit Design
5. Integrated circuit
6. Optoelectronics
7. Semiconductor
8. Semiconductor device
9. Embedded Systems



Electronics Technician performing a voltage check on a power circuit card in the air navigation equipment room aboard the aircraft carrier USS Abraham Lincoln *(CVN 72).*

1.1.2 Electronic devices and components

Main article: Electronic component

An electronic component is any physical entity in an electronic system used to affect the electrons or their associated fields in a manner consistent with the intended function of the electronic system. Components are generally intended to be connected together, usually by being soldered to a printed circuit board (PCB), to create an electronic circuit with a particular function (for example an amplifier, radio receiver, or oscillator). Components may be packaged singly, or in more complex groups as integrated circuits. Some common electronic components are capacitors, inductors, resistors, diodes, transistors, etc. Components are often categorized as active (e.g. transistors and thyristors) or passive (e.g. resistors, diodes, inductors and capacitors).

1.1.3 History of electronic components

Further information: Timeline of electrical and electronic engineering

Vacuum tubes (Thermionic valves) were one of the earliest electronic components. They were almost solely responsible for the electronics revolution of the first half of the Twentieth Century. They took electronics from parlor tricks and gave us radio, television, phonographs, radar, long distance telephony and much more. They played a leading role in the field of microwave and high power transmission as well as television receivers until the middle of the 1980s.[1] Since that time, solid state devices have all but completely taken over. Vacuum tubes are still used in some specialist applications such as high power RF amplifiers, cathode ray tubes, specialist audio equipment, guitar amplifiers and some microwave devices.

In April 1955 the IBM 608 was the first IBM product to use transistor circuits without any vacuum tubes and is believed to be the world's first all-transistorized calculator to be manufactured for the commercial market.[2][3] The 608 contained more than 3,000 germanium transistors. Thomas J. Watson Jr. ordered all future IBM products to use transistors in their design. From that time on transistors were almost exclusively used for computer logic and peripherals.

1.1.4 Types of circuits

Circuits and components can be divided into two groups: analog and digital. A particular device may consist of circuitry that has one or the other or a mix of the two types.

Analog circuits

Main article: Analog electronics

Most analog electronic appliances, such as radio receivers, are constructed from combinations of a few types of basic circuits. Analog circuits use a continuous range of voltage or current as opposed to discrete levels as in digital circuits.

Hitachi J100 adjustable frequency drive chassis

The number of different analog circuits so far devised is huge, especially because a 'circuit' can be defined as anything from a single component, to systems containing thousands of components.

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

One rarely finds modern circuits that are entirely analog. These days analog circuitry may use digital or even microprocessor techniques to improve performance. This type of circuit is usually called "mixed signal" rather than analog or digital.

Sometimes it may be difficult to differentiate between analog and digital circuits as they have elements of both linear and non-linear operation. An example is the comparator which takes in a continuous range of voltage but only outputs one of two levels as in a digital circuit. Similarly, an overdriven transistor amplifier can take on the characteristics of a controlled switch having essentially two levels of output. In fact, many digital circuits are actually implemented as variations of analog circuits similar to this example—after all, all aspects of the real physical world are essentially analog, so digital effects are only realized by constraining analog behavior.

Digital circuits

Main article: Digital electronics

Digital circuits are electric circuits based on a number of discrete voltage levels. Digital circuits are the most common physical representation of Boolean algebra, and are the basis of all digital computers. To most engineers, the terms "digital circuit", "digital system" and "logic" are interchangeable in the context of digital circuits. Most digital circuits use a binary system with two voltage levels labeled "0" and "1". Often logic "0" will be a lower voltage and referred to as "Low" while logic "1" is referred to as "High". However, some systems use the reverse definition ("0" is "High") or are current based. Quite often the logic designer may reverse these definitions from one circuit to the next as he sees fit to facilitate his design. The definition of the levels as "0" or "1" is arbitrary.

Ternary (with three states) logic has been studied, and some prototype computers made.

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

Building blocks:

- Logic gates
- Adders
- Flip-flops
- Counters
- Registers
- Multiplexers
- Schmitt triggers

Highly integrated devices:

- Microprocessors
- Microcontrollers
- Application-specific integrated circuit (ASIC)
- Digital signal processor (DSP)
- Field-programmable gate array (FPGA)

1.1.5 Heat dissipation and thermal management

Main article: Thermal management of electronic devices and systems

Heat generated by electronic circuitry must be dissipated to prevent immediate failure and improve long term reliability. Heat dissipation is mostly achieved by passive conduction/convection. Means to achieve greater dissipation include heat sinks and fans for air cooling, and other forms of computer cooling such as water cooling. These techniques use convection, conduction, and radiation of heat energy.

1.1.6 Noise

Main article: Electronic noise

Electronic noise is defined[4] as unwanted disturbances superposed on a useful signal that tend to obscure its information content. Noise is not the same as signal distortion caused by a circuit. Noise is associated with all electronic circuits. Noise may be electromagnetically or thermally generated, which can be decreased by lowering the operating temperature of the circuit. Other types of noise, such as shot noise cannot be removed as they are due to limitations in physical properties.

1.1.7 Electronics theory

Main article: Mathematical methods in electronics

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

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

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

1.1.8 Electronics lab

Main article: Electronic circuit simulation

Due to the complex nature of electronics theory, laboratory experimentation is an important part of the development of electronic devices. These experiments are used to test or verify the engineer's design and detect errors. Historically, electronics labs have consisted of electronics devices and equipment located in a physical space, although in more recent years the trend has been towards electronics lab simulation software, such as CircuitLogix, Multisim, and PSpice.

1.1.9 Computer aided design (CAD)

Main article: Electronic design automation

Today's electronics engineers have the ability to design circuits using premanufactured building blocks such as power supplies, semiconductors (i.e. semiconductor devices, such as transistors), and integrated circuits. Electronic design automation software programs include schematic capture programs and printed circuit board design programs. Popular names in the EDA software world are NI Multisim, Cadence (ORCAD), EAGLE PCB and Schematic, Mentor (PADS PCB and LOGIC Schematic), Altium (Protel), LabCentre Electronics (Proteus), gEDA, KiCad and many others.

1.1.10 Construction methods

Main article: Electronic packaging

Many different methods of connecting components have been used over the years. For instance, early electronics often used point to point wiring with components attached to wooden breadboards to construct circuits. Cordwood construction and wire wrap were other methods used. Most modern day electronics now use printed circuit boards made of materials such as FR4, or the cheaper (and less hard-wearing) Synthetic Resin Bonded Paper (SRBP, also known as Paxoline/Paxolin (trade marks) and FR2) - characterised by its brown colour. Health and environmental concerns associated with electronics assembly have gained increased attention in recent years, especially for products destined to the European Union, with its Restriction of Hazardous Substances Directive (RoHS) and Waste Electrical and Electronic Equipment Directive (WEEE), which went into force in July 2006.

1.1.11 Degradation

Rasberry crazy ants have been known to consume the insides of electrical wiring, and nest inside of electronics; they prefer DC to AC currents. This behavior is not well understood by scientists.[5]

1.1.12 See also

- Atomtronics
- Audio engineering
- Broadcast engineering
- Computer engineering
- Electronic engineering
- Electronics engineering technology
- Fuzzy electronics
- Index of electronics articles
- List of mechanical, electrical and electronic equipment manufacturing companies by revenue
- Marine electronics
- Power electronics
- Robotics

1.1.13 References

[1] Sōgo Okamura (1994). *History of Electron Tubes*. IOS Press. p. 5. ISBN 978-90-5199-145-1. Retrieved 5 December 2012.

[2] Bashe, Charles J.; et al. (1986). *IBM's Early Computers*. MIT. p. 386.

[3] Pugh, Emerson W.; Johnson, Lyle R.; Palmer, John H. (1991). *IBM's 360 and early 370 systems*. MIT Press. p. 34. ISBN 0-262-16123-0.

[4] IEEE Dictionary of Electrical and Electronics Terms ISBN 978-0-471-42806-0

[5] Andrew R Hickey (May 15, 2008). "'Crazy' Ant Invasion Frying Computer Equipment".

1.1.14 Further reading

- *The Art of Electronics* ISBN 978-0-521-37095-0

1.1.15 External links

- Electronics at DMOZ
- Navy 1998 Navy Electricity and Electronics Training Series (NEETS)
- DOE 1998 Electrical Science, Fundamentals Handbook, 4 vols.

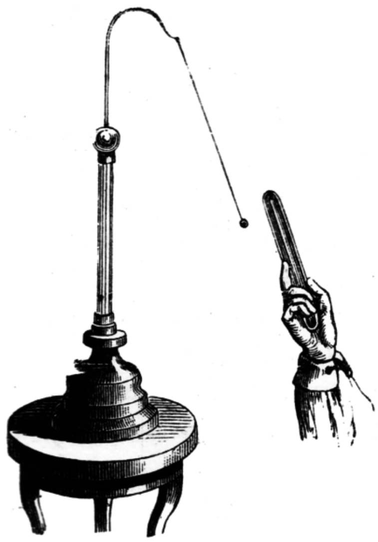
- Vol. 1, Basic Electrical Theory, Basic DC Theory
- Vol. 2, DC Circuits, Batteries, Generators, Motors
- Vol. 3, Basic AC Theory, Basic AC Reactive Components, Basic AC Power, Basic AC Generators
- Vol. 4, AC Motors, Transformers, Test Instruments & Measuring Devices, Electrical Distribution Systems

1.2 Voltage

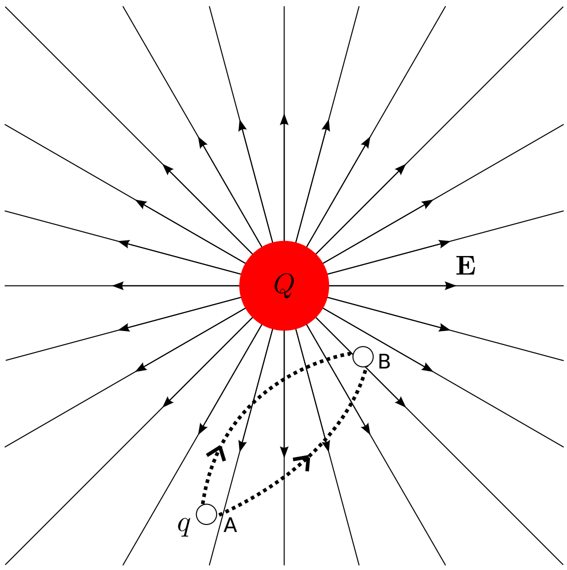
"Potential difference" redirects here. For other uses, see Potential.

Voltage, **electric potential difference**, **electric pressure** or **electric tension** (denoted ΔV or ΔU) is the difference in electric potential energy between two points per unit electric charge. The voltage between two points is equal to the work done per unit of charge against a static electric field to move the charge between two points and is measured in units of *volts* (a joule per coulomb).

Voltage can be caused by static electric fields, by electric current through a magnetic field, by time-varying magnetic fields, or some combination of these three.[1][2] A voltmeter can be used to measure the voltage (or potential difference) between two points in a system; often a common reference potential such as the ground of the system is used as one of the points. A voltage may represent either a source of energy (electromotive force), or lost, used, or stored energy (potential drop).



The electric field around the rod exerts a force on the charged pith ball, in an electroscope



In a static field, the work is independent of the path

1.2.1 Definition

Given two points in space, A and B, voltage is the difference in electric potential between those two points. From the definition of electric potential it follows that:

$$\Delta V_{BA} = V_B - V_A = -\int_{r_0}^{B} \vec{E} \cdot d\vec{l} - \left(-\int_{r_0}^{A} \vec{E} \cdot d\vec{l}\right)$$

$$= \int_{B}^{r_0} \vec{E} \cdot d\vec{l} + \int_{r_0}^{A} \vec{E} \cdot d\vec{l} = \int_{B}^{A} \vec{E} \cdot d\vec{l}$$

Voltage is electric potential energy per unit charge, measured in joules per coulomb (= volts). It is often referred to as "electric potential", which then must be distinguished from electric potential energy by noting that the "potential" is a "per-unit-charge" quantity. Like mechanical potential energy, the zero of potential can be chosen at any point, so the difference in voltage is the quantity which is physically meaningful. The difference in voltage measured when moving from point A to point B is equal to the work which would have to be done, per unit charge, against the electric field to move the charge from A to B. The voltage between the two ends of a path is the total energy required to move a small electric charge along that path, divided by the magnitude of the charge. Mathematically this is expressed as the line integral of the electric field and the time rate of change of magnetic field along that path. In the general case, both a static (unchanging) electric field and a dynamic (time-varying) electromagnetic field must be included in determining the voltage between two points.

Historically this quantity has also been called "tension"[3] and "pressure". Pressure is now obsolete but tension is still used, for example within the phrase "high tension" (HT) which is commonly used in thermionic valve (vacuum tube) based electronics.

Voltage is defined so that negatively charged objects are pulled towards higher voltages, while positively charged objects are pulled towards lower voltages. Therefore, the conventional current in a wire or resistor always flows from higher voltage to lower voltage. Current can flow from lower voltage to higher voltage, but only when a source of energy is present to "push" it against the opposing electric field. For example, inside a battery, chemical reactions provide the energy needed for current to flow from the negative to the positive terminal.

The electric field is not the only factor determining charge flow in a material, and different materials naturally develop electric potential differences at equilibrium (Galvani potentials). The electric potential of a material is not even a well defined quantity, since it varies on the subatomic scale. A more convenient definition of 'voltage' can be found instead in the concept of Fermi level. In this case the voltage between two bodies is the thermodynamic work required to move a unit of charge between them. This definition is practical since a real voltmeter actually measures this work, not differences in electric potential.

1.2.2 Volt

Main article: Volt

The volt (symbol: **V**) is the derived unit for electric potential, electric potential difference (voltage), and electromotive force.[4] The volt is named in honour of the Italian physicist Alessandro Volta (1745–1827), who invented the voltaic pile, possibly the first chemical battery.

1.2.3 Hydraulic analogy

Main article: Hydraulic analogy

A simple analogy for an electric circuit is water flowing in a closed circuit of pipework, driven by a mechanical pump. This can be called a "water circuit". Potential difference between two points corresponds to the pressure difference between two points. If the pump creates a pressure difference between two points, then water flowing from one point to the other will be able to do work, such as driving a turbine. Similarly, work can be done by an electric current driven by the potential difference provided by a battery. For example, the voltage provided by a sufficiently-charged automobile battery can "push" a large current through the windings of an automobile's starter motor. If the pump isn't working, it produces no pressure difference, and the turbine will not rotate. Likewise, if the automobile's battery is very weak or "dead" (or "flat"), then it will not turn the starter motor.

The hydraulic analogy is a useful way of understanding many electrical concepts. In such a system, the work done to move water is equal to the pressure multiplied by the volume of water moved. Similarly, in an electrical circuit, the work done to move electrons or other charge-carriers is equal to "electrical pressure" multiplied by the quantity of electrical charges moved. In relation to "flow", the larger the "pressure difference" between two points (potential difference or water pressure difference), the greater the flow between them (electric current or water flow). (See "Electric power".)

1.2.4 Applications

Working on high voltage power lines

Specifying a voltage measurement requires explicit or implicit specification of the points across which the voltage is measured. When using a voltmeter to measure potential difference, one electrical lead of the voltmeter must be connected to the first point, one to the second point.

A common use of the term "voltage" is in describing the voltage dropped across an electrical device (such as a resistor). The voltage drop across the device can be understood as the difference between measurements at each terminal of the device with respect to a common reference point (or ground). The voltage drop is the difference between the two readings. Two points in an electric circuit that are connected by an ideal conductor without resistance and not within a changing magnetic field have a voltage of zero. Any two points with the same potential may be connected by a conductor and no current will flow between them.

Addition of voltages

The voltage between *A* and *C* is the sum of the voltage between *A* and *B* and the voltage between *B* and *C*. The various voltages in a circuit can be computed using Kirchhoff's circuit laws.

When talking about alternating current (AC) there is a difference between instantaneous voltage and average voltage. Instantaneous voltages can be added for direct current (DC) and AC, but average voltages can be meaningfully added only when they apply to signals that all have the same frequency and phase.

1.2.5 Measuring instruments

Multimeter set to measure voltage

Instruments for measuring voltages include the voltmeter, the potentiometer, and the oscilloscope. The voltmeter works by measuring the current through a fixed resistor, which, according to Ohm's Law, is proportional to the voltage across the resistor. The potentiometer works by balancing the unknown voltage against a known voltage in a bridge circuit. The cathode-ray oscilloscope works by amplifying the voltage and using it to deflect an electron beam from a straight path, so that the deflection of the beam is proportional to the voltage.

1.2.6 Typical voltages

Main article: Mains electricity § Choice of voltage

A common voltage for flashlight batteries is 1.5 volts (DC). A common voltage for automobile batteries is 12 volts (DC).

Common voltages supplied by power companies to consumers are 110 to 120 volts (AC) and 220 to 240 volts (AC). The voltage in electric power transmission lines used to distribute electricity from power stations can be several hundred times greater than consumer voltages, typically 110 to 1200 kV (AC).

The voltage used in overhead lines to power railway locomotives is between 12 kV and 50 kV (AC).

1.2.7 Galvani potential vs. electrochemical potential

Main articles: Galvani potential, Electrochemical potential and Fermi level

Inside a conductive material, the energy of an electron is affected not only by the average electric potential, but also by the specific thermal and atomic environment that it is in. When a voltmeter is connected between two different types of metal, it measures not the electrostatic potential difference, but instead something else that is affected by thermodynamics.[5] The quantity measured by a voltmeter is the negative of difference of electrochemical potential of electrons (Fermi level) divided by electron charge, while the pure unadjusted electrostatic potential (not measurable with voltmeter) is sometimes called Galvani potential. The terms "voltage" and "electric potential" are ambiguous in that, in practice, they can refer to *either* of these in different contexts.

1.2.8 See also

- Alternating current (AC)
- Direct current (DC)
- Electric potential
- Electric shock
- Electrical measurements
- Electrochemical potential
- Fermi level
- High voltage
- Mains electricity (an article about domestic power supply voltages)
- Mains electricity by country (list of countries with mains voltage and frequency)
- Ohm's law

- Ohm
- Open-circuit voltage
- Phantom voltage

1.2.9 References

[1] Demetrius T. Paris and F. Kenneth Hurd, *Basic Electromagnetic Theory*, McGraw-Hill, New York 1969, ISBN 0-07-048470-8, pp. 512, 546

[2] P. Hammond, *Electromagnetism for Engineers*, p. 135, Pergamon Press 1969 OCLC 854336.

[3] "Tension". *CollinsLanguage*.

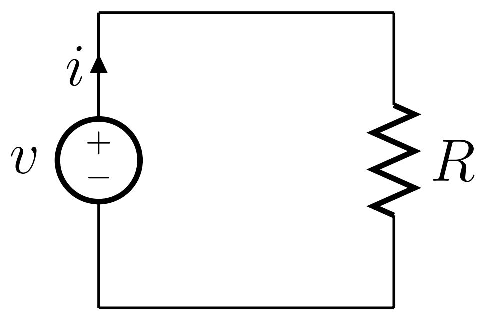
[4] "SI Brochure, Table 3 (Section 2.2.2)". BIPM. 2006. Retrieved 2007-07-29.

[5] Bagotskii, Vladimir Sergeevich (2006). *Fundamentals of electrochemistry*. p. 22. ISBN 978-0-471-70058-6.

1.2.10 External links

- Electrical voltage *V*, amperage *I*, resistivity *R*, impedance *Z*, wattage *P*
- Elementary explanation of voltage at NDT Resource Center

1.3 Electric current



A simple electric circuit, where current is represented by the letter i*. The relationship between the voltage (V), resistance (R), and current (I) is V=IR; this is known as Ohm's Law.*

An **electric current** is a flow of electric charge. In electric circuits this charge is often carried by moving electrons in a wire. It can also be carried by ions in an electrolyte, or by both ions and electrons such as in a plasma.[1]

The SI unit for measuring an electric current is the ampere, which is the flow of electric charge across a surface at the rate of one coulomb per second. Electric current is measured using a device called an ammeter.[2]

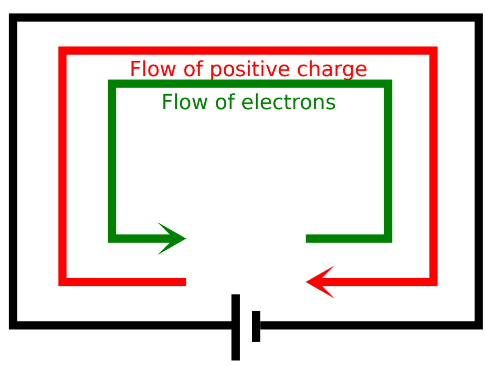
Electric currents cause Joule heating, which creates light in incandescent light bulbs. They also create magnetic fields, which are used in motors, inductors and generators.

The particles that carry the charge in an electric current are called charge carriers. In metals, one or more electrons from each atom are loosely bound to the atom, and can move freely about within the metal. These conduction electrons are the charge carriers in metal conductors.

1.3.1 Symbol

The conventional symbol for current is *I*, which originates from the French phrase *intensité de courant*, meaning *current intensity*.[3][4] Current intensity is often referred to simply as *current*.[5] The *I* symbol was used by André-Marie Ampère, after whom the unit of electric current is named, in formulating the eponymous Ampère's force law, which he discovered in 1820.[6] The notation travelled from France to Great Britain, where it became standard, although at least one journal did not change from using *C* to *I* until 1896.[7]

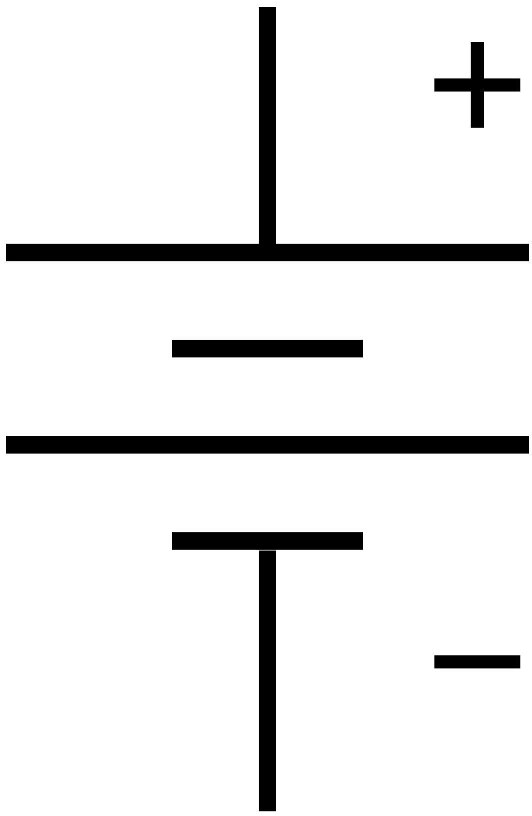
1.3.2 Conventions



The electrons, the charge carriers in an electrical circuit, flow in the opposite direction of the conventional electric current.

In metals, which make up the wires and other conductors in most electrical circuits, the positively charged atomic nuclei are held in a fixed position, and the electrons are free to move, carrying their charge from one place to another. In other materials, notably the semiconductors, the charge carriers can be positive *or* negative, depending on the dopant used. Positive and negative charge carriers may even be present at the same time, as happens in an electrochemical cell.

A flow of positive charges gives the same electric current, and has the same effect in a circuit, as an equal flow of negative charges in the opposite direction. Since current can be the flow of either positive or negative charges, or both, a convention is needed for the direction of current



The symbol for a battery in a circuit diagram.

that is independent of the type of charge carriers. The direction of *conventional current* is arbitrarily defined as the same direction as positive charges flow.

The consequence of this convention is that electrons, the charge carriers in metal wires and most other parts of electric circuits, flow in the opposite direction of conventional current flow in an electrical circuit.

Reference direction

Since the current in a wire or component can flow in either direction, when a variable I is defined to represent that current, the direction representing positive current must be specified, usually by an arrow on the circuit schematic diagram. This is called the *reference direction* of current I. If the current flows in the opposite direction, the variable I has a negative value.

When analyzing electrical circuits, the actual direction of current through a specific circuit element is usually unknown. Consequently, the reference directions of currents are often assigned arbitrarily. When the circuit is solved, a negative value for the variable means that the actual direction of current through that circuit element is opposite that of the chosen reference direction. In electronic circuits, the reference current directions are often chosen so that all currents are toward ground. This often corresponds to the actual current direction, because in many circuits the power supply voltage is positive with respect to ground.

1.3.3 Ohm's law

Main article: Ohm's law

Ohm's law states that the current through a conductor between two points is directly proportional to the potential difference across the two points. Introducing the constant of proportionality, the resistance,[8] one arrives at the usual mathematical equation that describes this relationship:[9]

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

where I is the current through the conductor in units of amperes, V is the potential difference measured *across* the conductor in units of volts, and R is the resistance of the conductor in units of ohms. More specifically, Ohm's law states that the R in this relation is constant, independent of the current.[10]

1.3.4 AC and DC

The abbreviations *AC* and *DC* are often used to mean simply *alternating* and *direct*, as when they modify *current* or *voltage*.[11][12]

Direct current

Main article: Direct current

Direct current (DC) is the unidirectional flow of electric charge. Direct current is produced by sources such as batteries, thermocouples, solar cells, and commutator-type electric machines of the dynamo type. Direct current may flow in a conductor such as a wire, but can also flow through semiconductors, insulators, or even through a vacuum as in electron or ion beams. The electric charge flows in a constant direction, distinguishing it from alternating current (AC). A term formerly used for *direct current* was **galvanic current**.[13]

Alternating current

Main article: Alternating current

In alternating current (AC, also ac), the movement of electric charge periodically reverses direction. In direct current (DC, also dc), the flow of electric charge is only in one direction.

AC is the form of electric power delivered to businesses and residences. The usual waveform of an AC power circuit is a sine wave. Certain applications use different waveforms, such as triangular or square waves. Audio and radio signals carried on electrical wires are also examples of alternating current. An important goal in these applications is recovery of information encoded (or *modulated*) onto the AC signal.

1.3.5 Occurrences

Natural observable examples of electrical current include lightning, static electricity, and the solar wind, the source of the polar auroras.

Man-made occurrences of electric current include the flow of conduction electrons in metal wires such as the overhead power lines that deliver electrical energy across long distances and the smaller wires within electrical and electronic equipment. Eddy currents are electric currents that occur in conductors exposed to changing magnetic fields. Similarly, electric currents occur, particularly in the surface, of conductors exposed to electromagnetic waves. When oscillating electric currents flow at the correct voltages within radio antennas, radio waves are generated.

In electronics, other forms of electric current include the flow of electrons through resistors or through the vacuum in a vacuum tube, the flow of ions inside a battery or a neuron, and the flow of holes within a semiconductor.

1.3.6 Current measurement

Current can be measured using an ammeter.

At the circuit level, there are various techniques that can be used to measure current:

- Shunt resistors[14]
- Hall effect current sensor transducers
- Transformers (however DC cannot be measured)
- Magnetoresistive field sensors[15]

1.3.7 Resistive heating

Main article: Joule heating

Joule heating, also known as *ohmic heating* and *resistive heating*, is the process by which the passage of an electric current through a conductor releases heat. It was first studied by James Prescott Joule in 1841. Joule immersed a length of wire in a fixed mass of water and measured the temperature rise due to a known current through the wire for a 30 minute period. By varying the current and the length of the wire he deduced that the heat produced was proportional to the square of the current multiplied by the electrical resistance of the wire.

$$Q \propto I^2 R$$

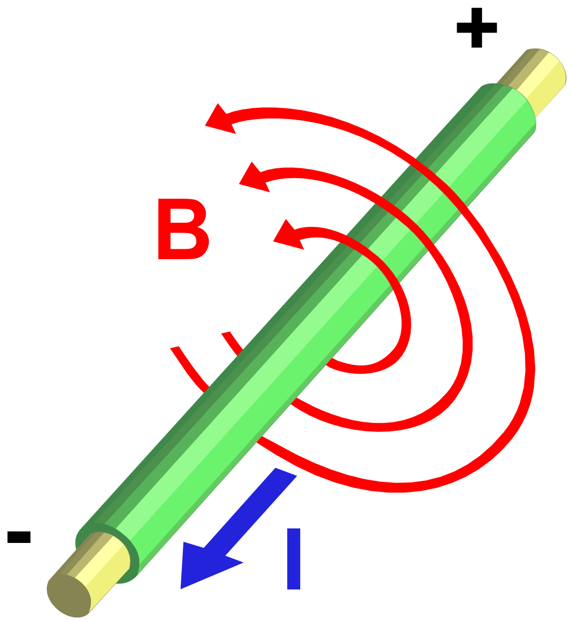
This relationship is known as Joule's First Law. The SI unit of energy was subsequently named the joule and given the symbol *J*. The commonly known unit of power, the watt, is equivalent to one joule per second.

1.3.8 Electromagnetism

Electromagnet

Main article: Electromagnet

In an electromagnet a coil, of a large number of circular turns of insulated wire, wrapped on a cylindrical core, behaves like a magnet when an electric current flows through it. When the current is switched off, the coil loses its magnetism immediately. We call such a device as an electromagnet.[16][17]



According to Ampère's law, an electric current produces a magnetic field.

Electric current produces a magnetic field. The magnetic field can be visualized as a pattern of circular field lines surrounding the wire that persists as long as there is current.

Magnetism can also produce electric currents. When a changing magnetic field is applied to a conductor, an Electromotive force (EMF) is produced, and when there is a suitable path, this causes current.

Electric current can be directly measured with a galvanometer, but this method involves breaking the electrical circuit, which is sometimes inconvenient. Current can also be measured without breaking the circuit by detecting the magnetic field associated with the current. Devices used for this include Hall effect sensors, current clamps, current transformers, and Rogowski coils.

Radio waves

Main article: Radio waves

When an electric current flows in a suitably shaped conductor at radio frequencies radio waves can be generated. These travel at the speed of light and can cause electric currents in distant conductors.

1.3.9 Conduction mechanisms in various media

Main article: Electrical conductivity

In metallic solids, electric charge flows by means of electrons, from lower to higher electrical potential. In other media, any stream of charged objects (ions, for example) may constitute an electric current. To provide a definition of current independent of the type of charge carriers, *conventional current* is defined as moving in the same direction as the positive charge flow. So, in metals where the charge carriers (electrons) are negative, conventional current is in the opposite direction as the electrons. In conductors where the charge carriers are positive, conventional current is in the same direction as the charge carriers.

In a vacuum, a beam of ions or electrons may be formed. In other conductive materials, the electric current is due to the flow of both positively and negatively charged particles at the same time. In still others, the current is entirely due to positive charge flow. For example, the electric currents in electrolytes are flows of positively and negatively charged ions. In a common lead-acid electrochemical cell, electric currents are composed of positive hydrogen ions (protons) flowing in one direction, and negative sulfate ions flowing in the other. Electric currents in sparks or plasma are flows of electrons as well as positive and negative ions. In ice and in certain solid electrolytes, the electric current is entirely composed of flowing ions.

Metals

A solid conductive metal contains mobile, or free electrons, which function as conduction electrons. These electrons are bound to the metal lattice but no longer to an individual atom. Metals are particularly conductive because there are a large number of these free electrons, typically one per atom in the lattice. Even with no external electric field applied, these electrons move about randomly due to thermal energy but, on average, there is zero net current within the metal. At room temperature, the average speed of these random motions is 10^6 metres per second.[18] Given a surface through which a metal wire passes, electrons move in both directions across the surface at an equal rate. As George Gamow wrote in his popular science 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.”

When a metal wire is connected across the two terminals of a DC voltage source such as a battery, the source places an electric field across the conductor. The moment contact is made, the free electrons of the conductor are forced to drift toward the positive terminal under the influence of this field. The free electrons are therefore the charge carrier in a typical solid conductor.

For a steady flow of charge through a surface, the current I (in amperes) can be calculated with the following equation:

$$I = \frac{Q}{t} \,,$$

where Q is the electric charge transferred through the surface over a time t. If Q and t are measured in coulombs and seconds respectively, I is in amperes.

More generally, electric current can be represented as the rate at which charge flows through a given surface as:

$$I = \frac{\mathrm{d}Q}{\mathrm{d}t} \,.$$

Electrolytes

Main article: Conductivity (electrolytic)

Electric currents in electrolytes are flows of electrically charged particles (ions). For example, if an electric field is placed across a solution of Na^+ and $Cl^−$ (and conditions are right) the sodium ions move towards the negative electrode (cathode), while the chloride ions move towards the positive electrode (anode). Reactions take place at both electrode surfaces, absorbing each ion.

Water-ice and certain solid electrolytes called proton conductors contain positive hydrogen ions ("protons") that are mobile. In these materials, electric currents are composed of moving protons, as opposed to the moving electrons in metals.

In certain electrolyte mixtures, brightly coloured ions are the moving electric charges. The slow progress of the colour makes the current visible.[19]

Gases and plasmas

In air and other ordinary gases below the breakdown field, the dominant source of electrical conduction is via relatively few mobile ions produced by radioactive gases, ultraviolet light, or cosmic rays. Since the electrical conductivity is low, gases are dielectrics or insulators. However, once the applied electric field approaches the breakdown value, free electrons become sufficiently accelerated by the electric field to create additional free electrons by colliding, and ionizing, neutral gas atoms or molecules in a process called avalanche breakdown. The breakdown process forms a plasma that contains enough mobile electrons and positive ions to make it an electrical conductor. In the process, it forms a light emitting conductive path, such as a spark, arc or lightning.

Plasma is the state of matter where some of the electrons in a gas are stripped or “ionized” from their molecules or atoms. A plasma can be formed by high temperature, or by application of a high electric or alternating magnetic field as noted above. Due to their lower mass, the electrons in a plasma accelerate more quickly in response to an electric field than the heavier positive ions, and hence carry the bulk of the current. The free ions recombine to create new chemical compounds (for example, breaking atmospheric oxygen into single oxygen [$O_2 \rightarrow 2O$], which then recombine creating ozone [O_3]).[20]

Vacuum

Since a "perfect vacuum" contains no charged particles, it normally behaves as a perfect insulator. However, metal electrode surfaces can cause a region of the vacuum to become conductive by injecting free electrons or ions through either field electron emission or thermionic emission. Thermionic emission occurs when the thermal energy exceeds the metal’s work function, while field electron emission occurs when the electric field at the surface of the metal is high enough to cause tunneling, which results in the ejection of free electrons from the metal into the vacuum. Externally heated electrodes are often used to generate an electron cloud as in the filament or indirectly heated cathode of vacuum tubes. Cold electrodes can also spontaneously produce electron clouds via thermionic emission when small incandescent regions (called **cathode spots** or **anode spots**) are formed. These are incandescent regions of the electrode surface that are created by a localized high current. These regions may be initiated by field electron emission, but are then sustained by localized thermionic emission once a vacuum arc forms. These small electron-emitting regions can form quite rapidly, even explosively, on a metal surface subjected to a high electrical field. Vacuum tubes and sprytrons are some of the electronic switching and amplifying devices based on vacuum conductivity.

Superconductivity

Main article: Superconductivity

Superconductivity is a phenomenon of exactly zero electrical resistance and expulsion of magnetic fields occurring in certain materials when cooled below a characteristic critical temperature. It was discovered by Heike Kamerlingh Onnes on April 8, 1911 in Leiden. Like ferromagnetism and atomic spectral lines, superconductivity is a quantum mechanical phenomenon. It is characterized by the Meissner effect, the complete ejection of magnetic field lines from the interior of the superconductor as it transitions into the superconducting state. The occurrence of the Meissner effect indicates that superconductivity cannot be understood simply as the idealization of *perfect conductivity* in classical physics.

Semiconductor

Main article: Semiconductor

In a semiconductor it is sometimes useful to think of the current as due to the flow of positive "holes" (the mobile positive charge carriers that are places where the semiconductor crystal is missing a valence electron). This is the case in a p-type semiconductor. A semiconductor has electrical conductivity intermediate in magnitude between that of a conductor and an insulator. This means a conductivity roughly in the range of 10^{-2} to 10^{4} siemens per centimeter ($S{\cdot}cm^{-1}$).

In the classic crystalline semiconductors, electrons can have energies only within certain bands (i.e. ranges of levels of energy). Energetically, these bands are located between the energy of the ground state, the state in which electrons are tightly bound to the atomic nuclei of the material, and the free electron energy, the latter describing the energy required for an electron to escape entirely from the material. The energy bands each correspond to a large number of discrete quantum states of the electrons, and most of the states with low energy (closer to the nucleus) are occupied, up to a particular band called the *valence band*. Semiconductors and insulators are distinguished from metals because the valence band in any given metal is nearly filled with electrons under usual operating conditions, while very few (semiconductor) or virtually none (insulator) of them are available in the *conduction band*, the band immediately above the valence band.

The ease of exciting electrons in the semiconductor from the valence band to the conduction band depends on the band gap between the bands. The size of this energy band gap serves as an arbitrary dividing line (roughly 4 eV) between semiconductors and insulators.

With covalent bonds, an electron moves by hopping to a neighboring bond. The Pauli exclusion principle requires that the electron be lifted into the higher anti-bonding state of that bond. For delocalized states, for example in one dimension – that is in a nanowire, for every energy there is a state with electrons flowing in one direction and another state with the electrons flowing in the other. For a net current to flow, more states for one direction than for the other direction must be occupied. For this to occur, energy is required, as in the semiconductor the next higher states lie above the band gap. Often this is stated as: full bands do not contribute to the electrical conductivity. However, as a semiconductor's temperature rises above absolute zero, there is more energy in the semiconductor to spend on lattice vibration and on exciting electrons into the conduction band. The current-carrying electrons in the conduction band are known as *free electrons*, though they are often simply called *electrons* if that is clear in context.

1.3.10 Current density and Ohm's law

Main article: Current density

Current density is a measure of the density of an electric current. It is defined as a vector whose magnitude is the electric current per cross-sectional area. In SI units, the current density is measured in amperes per square metre.

$$I = \int \vec{J} \cdot d\vec{A}$$

where I is current in the conductor, $\vec{J}$ is the current density, and $d\vec{A}$ is the differential cross-sectional area vector.

The current density (current per unit area) $\vec{J}$ in materials with finite resistance is directly proportional to the electric field $\vec{E}$ in the medium. The proportionality constant is called the conductivity σ of the material, whose value depends on the material concerned and, in general, is dependent on the temperature of the material:

$$\vec{J} = \sigma\vec{E}$$

The reciprocal of the conductivity σ of the material is called the resistivity ρ of the material and the above equation, when written in terms of resistivity becomes:

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

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

Conduction in semiconductor devices may occur by a combination of drift and diffusion, which is proportional to diffusion constant D and charge density α_q . The current density is then:

$$J = \sigma E + Dq\nabla n,$$

with q being the elementary charge and n the electron density. The carriers move in the direction of decreasing concentration, so for electrons a positive current results for a positive density gradient. If the carriers are holes, replace electron density n by the negative of the hole density p .

In linear anisotropic materials, σ, ϱ and D are tensors.

In linear materials such as metals, and under low frequencies, the current density across the conductor surface is uniform. In such conditions, Ohm's law states that the current is directly proportional to the potential difference between two ends (across) of that metal (ideal) resistor (or other ohmic device):

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

where I is the current, measured in amperes; V is the potential difference, measured in volts; and R is the resistance, measured in ohms. For alternating currents, especially at higher frequencies, skin effect causes the current to spread unevenly across the conductor cross-section, with higher density near the surface, thus increasing the apparent resistance.

1.3.11 Drift speed

The mobile charged particles within a conductor move constantly in random directions, like the particles of a gas. To create a net flow of charge, the particles must also move together with an average drift rate. Electrons are the charge carriers in metals and they follow an erratic path, bouncing from atom to atom, but generally drifting in the opposite direction of the electric field. The speed they drift at can be calculated from the equation:

$$I = nAvQ,$$

where

I is the electric current

n is number of charged particles per unit volume (or charge carrier density)

A is the cross-sectional area of the conductor

v is the drift velocity, and

Q is the charge on each particle.

Typically, electric charges in solids flow slowly. For example, in a copper wire of cross-section 0.5 mm^2, carrying a current of 5 A, the drift velocity of the electrons is on the order of a millimetre per second. To take a different example, in the near-vacuum inside a cathode ray tube, the electrons travel in near-straight lines at about a tenth of the speed of light.

Any accelerating electric charge, and therefore any changing electric current, gives rise to an electromagnetic wave that propagates at very high speed outside the surface of the conductor. This speed is usually a significant fraction of the speed of light, as can be deduced from Maxwell's Equations, and is therefore many times faster than the drift velocity of the electrons. For example, in AC power lines, the waves of electromagnetic energy propagate through the space between the wires, moving from a source to a distant load, even though the electrons in the wires only move back and forth over a tiny distance.

The ratio of the speed of the electromagnetic wave to the speed of light in free space is called the velocity factor, and depends on the electromagnetic properties of the conductor and the insulating materials surrounding it, and on their shape and size.

The magnitudes (but, not the natures) of these three velocities can be illustrated by an analogy with the three similar velocities associated with gases.

- The low drift velocity of charge carriers is analogous to air motion; in other words, winds.
- The high speed of electromagnetic waves is roughly analogous to the speed of sound in a gas (these waves move through the medium much faster than any individual particles do)
- The random motion of charges is analogous to heat – the thermal velocity of randomly vibrating gas particles.

1.3.12 See also

- Current 3-vector
- Direct current
- Electric shock
- Electrical measurements
- History of electrical engineering
- Hydraulic analogy
- International System of Quantities
- SI electromagnetism units

1.3.13 References

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[5] K. S. Suresh Kumar, *Electric Circuit Analysis*, Pearson Education India, 2013, ISBN 9332514100, section 1.2.3 "'Current intensity' is usually referred to as 'current' itself."

[6] A-M Ampère, *Recuil d'Observations Électro-dynamiques*, p. 56, Paris: Chez Crochard Libraire 1822 (in French).

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[17] From the book/ We And Our World

[18] "The Mechanism Of Conduction In Metals", Think Quest.

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[20] "Lab Note #106 *Environmental Impact of Arc Suppression*". Arc Suppression Technologies. April 2011. Retrieved March 15, 2012.

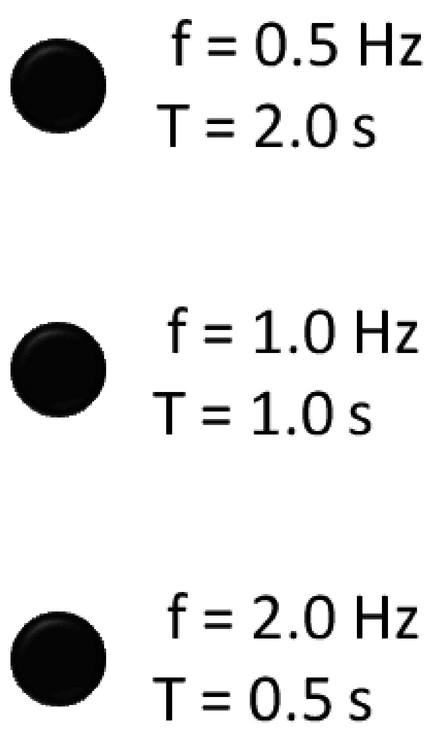
1.3.14 External links

- Allaboutcircuits.com, a useful site introducing electricity and electronics

1.4 Frequency

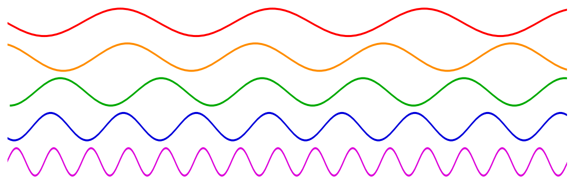
For other uses, see Frequency (disambiguation).
This article is about the rates of waves, oscillations, and vibrations. For the rates of non-cyclic phenomena, see Aperiodic frequency. For the general concept beyond the temporal domain, see Frequency (statistics).
For a broader coverage related to this topic, see Temporal rate.

Frequency is the number of occurrences of a repeating event per unit time.[1] It is also referred to as **temporal frequency**, which emphasizes the contrast to spatial frequency and angular frequency. The **period** is the duration of time of one cycle in a repeating event, so the period is the reciprocal of the frequency.[2] For example, if a newborn baby's heart beats at a frequency of 120 times a minute, its period – the interval between beats – is half a second (60 seconds (i.e., a minute) divided by 120 beats). Frequency is an important parameter used in science and engineering to specify the rate of oscillatory and vibratory phenomena, such as mechanical vibrations, audio (sound) signals, radio waves, and light.



Three cyclically flashing dots from lowest frequency (top) to highest frequency (bottom). For each dot, "f" is the frequency in hertz (Hz) – meaning the number of times per second (i.e. cycles per second) that it flashes – while "T" is the flashes' period in seconds (s), meaning the number of seconds per cycle. Each T and f are reciprocal.

1.4.1 Definitions



As time elapses – represented here as a movement from left to right, i.e. horizontally – the five sinusoidal waves shown vary regularly (i.e. cycle), but at different rates. The red wave (top) has the lowest frequency (i.e. varies at the slowest rate) while the purple wave (bottom) has the highest frequency (varies at the fastest rate).

For cyclical processes, such as rotation, oscillations, or waves, frequency is defined as a number of cycles per unit time. In physics and engineering disciplines, such as optics, acoustics, and radio, frequency is usually denoted by a Latin letter f or by the Greek letter ν or ν (nu) (see e.g. Planck's formula). The period, usually denoted by T, is the duration of one cycle, and is the reciprocal of the frequency f:

$$f = \frac{1}{T}.$$

1.4.2 Units

The SI unit of frequency is the hertz (Hz), named after the German physicist Heinrich Hertz; one hertz means that an event repeats once per second. A previous name for this unit was cycles per second (cps). The SI unit for period is the second.

A traditional unit of measure used with rotating mechanical devices is revolutions per minute, abbreviated r/min or rpm. 60 rpm equals one hertz.[3]

1.4.3 Period versus frequency

As a matter of convenience, longer and slower waves, such as ocean surface waves, tend to be described by wave period rather than frequency. Short and fast waves, like audio and radio, are usually described by their frequency instead of period. These commonly used conversions are listed below:

1.4.4 Related types of frequency

For other uses, see Frequency (disambiguation).

- Angular frequency, usually denoted by the Greek letter ω (omega), is defined as the rate of change of angular displacement, θ, (during rotation), or the rate of change of the phase of a sinusoidal waveform (e.g. in oscillations and waves), or as the rate of change of the argument to the sine function:

  $$y(t) = \sin(\theta(t)) = \sin(\omega t) = \sin(2\pi f t)$$

  $$\frac{\mathrm{d}\theta}{\mathrm{d}t} = \omega = 2\pi f$$

  Angular frequency is commonly measured in radians per second (rad/s) but, for discrete-time signals, can also be expressed as radians per sample time, which is a dimensionless quantity.

- Spatial frequency is analogous to temporal frequency, but the time axis is replaced by one or more spatial displacement axes. E.g.:

  $$y(t) = \sin(\theta(t, x)) = \sin(\omega t + kx)$$

  $$\frac{\mathrm{d}\theta}{\mathrm{d}x} = k$$

  Wavenumber, k, sometimes means the spatial frequency analogue of angular temporal frequency. In case of more than one spatial dimension, wavenumber is a vector quantity.

1.4.5 In wave propagation

Further information: Wave propagation

For periodic waves in nondispersive media (that is, media in which the wave speed is independent of frequency), frequency has an inverse relationship to the wavelength, λ (lambda). Even in dispersive media, the frequency f of a sinusoidal wave is equal to the phase velocity v of the wave divided by the wavelength λ of the wave:

$$f = \frac{v}{\lambda}.$$

In the special case of electromagnetic waves moving through a vacuum, then $v = c$, where c is the speed of light in a vacuum, and this expression becomes:

$$f = \frac{c}{\lambda}.$$

When waves from a monochrome source travel from one medium to another, their frequency remains the same—only their wavelength and speed change.

1.4.6 Measurement

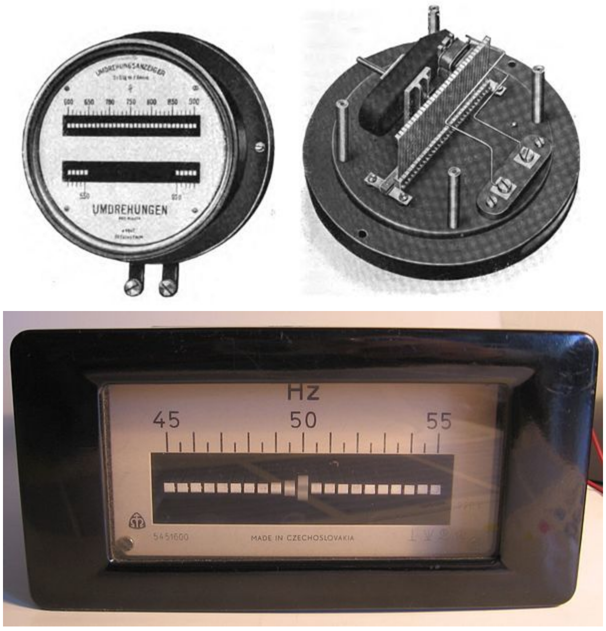
See also: Frequency meter

By counting

Calculating the frequency of a repeating event is accomplished by counting the number of times that event occurs within a specific time period, then dividing the count by the length of the time period. For example, if 71 events occur within 15 seconds the frequency is:

$$f = \frac{71}{15\,\mathrm{s}} \approx 4.7\,\mathrm{Hz}$$

If the number of counts is not very large, it is more accurate to measure the time interval for a predetermined number of occurrences, rather than the number of occurrences within a specified time.[4] The latter method introduces a random error into the count of between zero and one count, so on average half a count. This is called *gating error* and causes an average error in the calculated frequency of $\Delta f = 1/(2\,T_m)$, or a fractional error of $\Delta f / f = 1/(2 f T_m)$ where T_m is the timing interval and f is the measured frequency. This error decreases with frequency, so it is a problem at low frequencies where the number of counts N is small.



A resonant-reed frequency meter, an obsolete device used from about 1900 to the 1940s for measuring the frequency of alternating current. It consists of a strip of metal with reeds of graduated lengths, vibrated by an electromagnet. When the unknown frequency is applied to the electromagnet, the reed which is resonant at that frequency will vibrate with large amplitude, visible next to the scale.

By stroboscope

An older method of measuring the frequency of rotating or vibrating objects is to use a stroboscope. This is an intense repetitively flashing light (strobe light) whose frequency can be adjusted with a calibrated timing circuit. The strobe light is pointed at the rotating object and the frequency adjusted up and down. When the frequency of the strobe equals the frequency of the rotating or vibrating object, the object completes one cycle of oscillation and returns to its original position between the flashes of light, so when illuminated by the strobe the object appears stationary. Then the frequency can be read from the calibrated readout on the stroboscope. A downside of this method is that an object rotating at an integer multiple of the strobing frequency will also appear stationary.

By frequency counter

Higher frequencies are usually measured with a frequency counter. This is an electronic instrument which measures the frequency of an applied repetitive electronic signal and displays the result in hertz on a digital display. It uses digital logic to count the number of cycles during a time interval established by a precision quartz time base. Cyclic processes that are not electrical in nature, such as the rotation rate of a shaft, mechanical vibrations, or sound waves, can be converted to a repetitive electronic signal by transducers and the signal applied to a frequency counter. Frequency counters can currently cover the range up to about 100 GHz. This represents the limit of direct counting methods; frequencies above this must be measured by indirect methods.

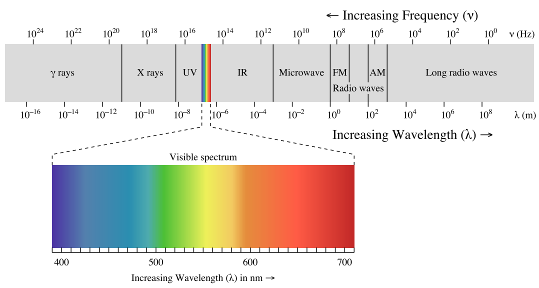
Modern frequency counter

Heterodyne methods

Above the range of frequency counters, frequencies of electromagnetic signals are often measured indirectly by means of heterodyning (frequency conversion). A reference signal of a known frequency near the unknown frequency is mixed with the unknown frequency in a nonlinear mixing device such as a diode. This creates a heterodyne or “beat” signal at the difference between the two frequencies. If the two signals are close together in frequency the heterodyne is low enough to be measured by a frequency counter. This process only measures the difference between the unknown frequency and the reference frequency, which must be determined by some other method. To reach higher frequencies, several stages of heterodyning can be used. Current research is extending this method to infrared and light frequencies (optical heterodyne detection).

1.4.7 Examples

Light



Complete spectrum of electromagnetic radiation with the visible portion highlighted

Main articles: Light and Electromagnetic radiation

Visible light is an electromagnetic wave, consisting of oscillating electric and magnetic fields traveling through space. The frequency of the wave determines its color: 4×10^{14} Hz is red light, 8×10^{14} Hz is violet light, and between these (in the range 4-8×10^{14} Hz) are all the other colors of the rainbow. An electromagnetic wave can have a frequency less than 4×10^{14} Hz, but it will be invisible to the human eye; such waves are called infrared (IR) radiation. At even lower frequency, the wave is called a microwave, and at still lower frequencies it is called a radio wave. Likewise, an electromagnetic wave can have a frequency higher than 8×10^{14} Hz, but it will be invisible to the human eye; such waves are called ultraviolet (UV) radiation. Even higher-frequency waves are called X-rays, and higher still are gamma rays.

All of these waves, from the lowest-frequency radio waves to the highest-frequency gamma rays, are fundamentally the same, and they are all called electromagnetic radiation. They all travel through a vacuum at the same speed (the speed of light), giving them wavelengths inversely proportional to their frequencies.

$$c = f\lambda$$

where c is the speed of light (c in a vacuum, or less in other media), f is the frequency and λ is the wavelength.

In dispersive media, such as glass, the speed depends somewhat on frequency, so the wavelength is not quite inversely proportional to frequency.

Sound

Main article: Audio frequency

Sound propagates as mechanical vibration waves of pressure and displacement, in air or other substances.[5] Frequency is the property of sound that most determines pitch.[6]

The frequencies an ear can hear are limited to a specific range of frequencies. The audible frequency range for humans is typically given as being between about 20 Hz and 20,000 Hz (20 kHz), though the high frequency limit usually reduces with age. Other species have different hearing ranges. For example, some dog breeds can perceive vibrations up to 60,000 Hz.[7]

In many media, such as air, the speed of sound is approximately independent of frequency, so the wavelength of the sound waves (distance between repetitions) is approximately inversely proportional to frequency.

Line current

Main article: Utility frequency

In Europe, Africa, Australia, Southern South America, most of Asia, and Russia, the frequency of the alternating current in household electrical outlets is 50 Hz (close to the tone G), whereas in North America and Northern South America, the frequency of the alternating current in household electrical outlets is 60 Hz (between the tones B♭ and B; that is, a minor third above the European frequency). The frequency of the 'hum' in an audio recording can show where the recording was made, in countries using a European, or an American, grid frequency.

1.4.8 See also

See also: Frequency (disambiguation)
See also: Category:Units of frequency.

- Audio frequency
- Bandwidth (signal processing)
- Cutoff frequency
- Downsampling
- Electronic filter
- Frequency band
- Frequency converter
- Frequency domain
- Frequency distribution
- Frequency extender
- Frequency grid
- Frequency modulation
- Frequency spectrum
- Interaction frequency
- Natural frequency
- Negative frequency
- Periodicity (disambiguation)
- Pink noise
- Preselector
- Radar signal characteristics
- Signaling (telecommunications)
- Spread spectrum
- Spectral component
- Transverter
- Upsampling
- Quefrency

1.4.9 Notes and references

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1.4.10 Further reading

- Giancoli, D.C. (1988). *Physics for Scientists and Engineers* (2nd ed.). Prentice Hall. ISBN 0-13-669201-X.

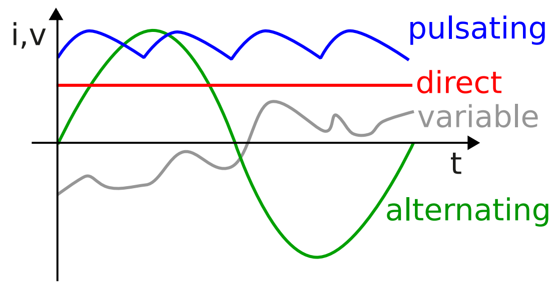
1.4.11 External links

- Conversion: frequency to wavelength and back
- Conversion: period, cycle duration, periodic time to frequency
- Keyboard frequencies = naming of notes - The English and American system versus the German system
- Teaching resource for 14-16yrs on sound including frequency
- A simple tutorial on how to build a frequency meter
- Frequency - diracdelta.co.uk – JavaScript calculation.

1.5 Direct current

"LVDC" redirects here. For the computer, see Saturn Launch Vehicle Digital Computer.

Direct current (**DC**) is the unidirectional flow of electric charge. Direct current is produced by sources such as batteries, power supplies, thermocouples, solar cells, or dynamos. Direct current may flow in a conductor such as a wire, but can also flow through semiconductors, insulators, or even through a vacuum as in electron or ion beams. The electric current flows in a constant direction, distinguishing it from alternating current (AC). A term formerly used for this type of current was **galvanic current**.[1]



Direct Current (red line). The horizontal axis measures time; the vertical, current or voltage.

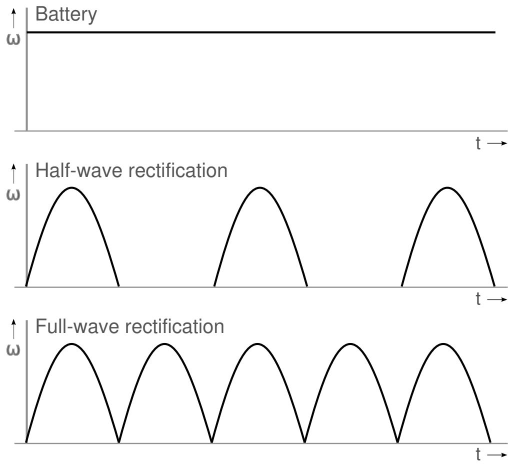
The abbreviations *AC* and *DC* are often used to mean simply *alternating* and *direct*, as when they modify *current* or *voltage*.[2][3]

Direct current may be obtained from an alternating current supply by use of a rectifier, which contains electronic elements (usually) or electromechanical elements (historically) that allow current to flow only in one direction. Direct current may be converted into alternating current with an inverter or a motor-generator set.

Direct current is used to charge batteries and as power supply for electronic systems. Very large quantities of direct-current power are used in production of aluminum and other electrochemical processes. It is also used for some railways, especially in urban areas. High-voltage direct current is used to transmit large amounts of power from remote generation sites or to interconnect alternating current power grids.

1.5.1 History

The first commercial electric power transmission (developed by Thomas Edison in the late nineteenth century) used direct current. Because of the significant advantages of alternating current over direct current in transforming and transmission, electric power distribution is nearly all alternating current today. In the mid-1950s, high-voltage direct current transmission was developed, and is now an option instead of long-distance high voltage alternating current systems. For long distance underseas cables (e.g. between countries, such as NorNed), this DC option is the only technically feasible option. For applications requiring direct current, such as third rail power systems, alternating current is distributed to a substation, which utilizes a rectifier to convert the power to direct current. *See War of Currents*.



Types of direct current

1.5.2 Various definitions

The term *DC* is used to refer to power systems that use only one polarity of voltage or current, and to refer to the constant, zero-frequency, or slowly varying local mean value of a voltage or current.[4] For example, the voltage across a DC voltage source is constant as is the current through a DC current source. The DC solution of an electric circuit is the solution where all voltages and currents are constant. It can be shown that any stationary voltage or current waveform can be decomposed into a sum of a DC component and a zero-mean time-varying component; the DC component is defined to be the expected value, or the average value of the voltage or current over all time.

Although DC stands for “direct current”, DC often refers to “constant polarity”. Under this definition, DC voltages can vary in time, as seen in the raw output of a rectifier or the fluctuating voice signal on a telephone line.

Some forms of DC (such as that produced by a voltage regulator) have almost no variations in voltage, but may still have variations in output power and current.

1.5.3 Circuits

A direct current circuit is an electrical circuit that consists of any combination of constant voltage sources, constant current sources, and resistors. In this case, the circuit voltages and currents are independent of time. A particular circuit voltage or current does not depend on the past value of any circuit voltage or current. This implies that the system of equations that represent a DC circuit do not involve integrals or derivatives with respect to time.

If a capacitor or inductor is added to a DC circuit, the resulting circuit is not, strictly speaking, a DC circuit. However, most such circuits have a DC solution. This solution gives the circuit voltages and currents when the circuit is in DC steady state. Such a circuit is represented by a system of differential equations. The solution to these equations usually contain a time varying or transient part as well as constant or steady state part. It is this steady state part that is the DC solution. There are some circuits that do not have a DC solution. Two simple examples are a constant current source connected to a capacitor and a constant voltage source connected to an inductor.

In electronics, it is common to refer to a circuit that is powered by a DC voltage source such as a battery or the output of a DC power supply as a DC circuit even though what is meant is that the circuit is DC powered.

1.5.4 Applications

Domestic

This symbol is found on many electronic devices that either require or produce direct current.

DC is commonly found in many extra-low voltage applications and some low-voltage applications, especially where these are powered by batteries or solar power systems (since both can produce only DC).

Most electronic circuits require a DC power supply.

Domestic DC installations usually have different types of sockets, connectors, switches, and fixtures from those suitable for alternating current. This is mostly due to the lower voltages used, resulting in higher currents to produce the same amount of power.

It is usually important with a DC appliance to observe polarity, unless the device has a diode bridge to correct for this.

Automotive

Most automotive applications use DC. The alternator is an AC device which uses a rectifier to produce DC. Usually 12 V DC are used, but a few have a 6 V (e.g. classic VW Beetle) or a 42 V electrical system.

Telecommunication

Through the use of a DC-DC converter, higher DC voltages such as 48 V to 72 V DC can be stepped down to 36

V, 24 V, 18 V, 12 V, or 5 V to supply different loads. In a telecommunications system operating at 48 V DC, it is generally more efficient to step voltage down to 12 V to 24 V DC with a DC-DC converter and power equipment loads directly at their native DC input voltages, versus operating a 48 V DC to 120 V AC inverter to provide power to equipment.

Many telephones connect to a twisted pair of wires, and use a bias tee to internally separate the AC component of the voltage between the two wires (the audio signal) from the DC component of the voltage between the two wires (used to power the phone).

Telephone exchange communication equipment, such as DSLAMs, uses standard −48 V DC power supply. The negative polarity is achieved by grounding the positive terminal of power supply system and the battery bank. This is done to prevent electrolysis depositions.

High-voltage power transmission

Main article: High-voltage direct current

High-voltage direct current (HVDC) electric power transmission systems use DC for the bulk transmission of electrical power, in contrast with the more common alternating current systems. For long-distance transmission, HVDC systems may be less expensive and suffer lower electrical losses.

Other

Applications using fuel cells (mixing hydrogen and oxygen together with a catalyst to produce electricity and water as byproducts) also produce only DC.

Light aircraft electrical systems are typically 12 V or 28 V DC.

1.5.5 Trivia

The Unicode code point for the direct current symbol, found in the Miscellaneous Technical block, is U+2393 (⎓).

1.5.6 See also

- Electric current
- High-voltage direct current power transmission.
- Alternating current
- DC offset
- Neutral direct-current telegraph system

1.5.7 References

[1] Andrew J. Robinson, Lynn Snyder-Mackler (2007). *Clinical Electrophysiology: Electrotherapy and Electrophysiologic Testing* (3rd ed.). Lippincott Williams & Wilkins. p. 10. ISBN 978-0-7817-4484-3.

[2] N. N. Bhargava and D. C. Kulshrishtha (1984). *Basic Electronics & Linear Circuits*. Tata McGraw-Hill Education. p. 90. ISBN 978-0-07-451965-3.

[3] National Electric Light Association (1915). *Electrical meterman's handbook*. Trow Press. p. 81.

[4] Roger S. Amos, Geoffrey William Arnold Dummer (1999). *Newnes Dictionary of Electronic* (4th ed.). Newnes. p. 83. ISBN 0-7506-4331-5.

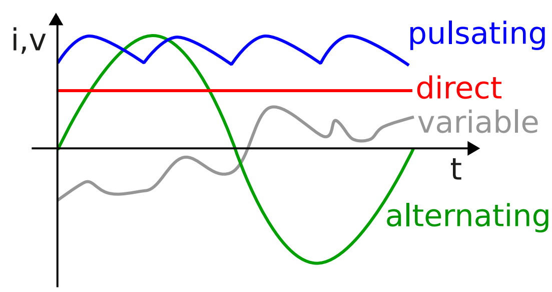
1.5.8 External links

- "*AC/DC: What's the Difference?*".
- "DC And AC Supplies" (PDF). ITACA. External link in |publisher= (help)

1.6 Alternating current

"Effective power" redirects here. For the iOS 8 bug, see SpringBoard § "effective. Power" bug.

Alternating current (**AC**), is an electric current in



Alternating current (green curve). The horizontal axis measures time; the vertical, current or voltage.

which the flow of electric charge periodically reverses direction, whereas in direct current (**DC**, also **dc**), the flow of electric charge is only in one direction. The abbreviations *AC* and *DC* are often used to mean simply *alternating* and *direct*, as when they modify *current* or *voltage*.[1][2]

AC is the form in which electric power is delivered to businesses and residences. The usual waveform of alternating current in most electric power circuits is a sine wave. In certain applications, different waveforms are used, such as triangular or square waves.

Audio and radio signals carried on electrical wires are also examples of alternating current. These types of alternating current carry information encoded (or modulated) onto the AC signal, such as sound (audio) or images (video). These currents typically alternate at higher frequencies than those used in power transmission.

1.6.1 Transmission, distribution, and domestic power supply

Main articles: Electric power transmission and Electric power distribution

Electric power is distributed as alternating current because AC voltage may be increased or decreased with a transformer. This allows the power to be transmitted through power lines efficiently at high voltage, which reduces the power lost as heat due to resistance of the wire, and transformed to a lower, safer, voltage for use. Use of a higher voltage leads to significantly more efficient transmission of power. The power losses (P_{L}) in a conductor are a product of the square of the current (I) and the resistance (R) of the conductor, described by the formula

$$P_{\mathrm{L}} = I^2 R \,.$$

This means that when transmitting a fixed power on a given wire, if the current is doubled, the power loss will be four times greater.

The power transmitted is equal to the product of the current and the voltage (assuming no phase difference); that is,

$$P_{\mathrm{T}} = IV \,.$$

Consequently, power transmitted at a higher voltage requires less loss-producing current than for the same power at a lower voltage. Power is often transmitted at hundreds of kilovolts, and transformed to 100-240 volts for domestic use.

High voltages have disadvantages, the main one being the increased insulation required, and generally increased difficulty in their safe handling. In a power plant, power is generated at a convenient voltage for the design of a generator, and then stepped up to a high voltage for transmission. Near the loads, the transmission voltage is stepped down to the voltages used by equipment. Consumer voltages vary depending on the country and size of load, but generally motors and lighting are built to use up to a few hundred volts between phases.

The utilization voltage delivered to equipment such as lighting and motor loads is standardized, with an allowable range of voltage over which equipment is expected to operate. Standard power utilization voltages and percentage tolerance vary in the different mains power systems found in the world.

High voltage transmission lines deliver power from electric generation plants over long distances using alternating current. These particular lines are located in eastern Utah.

High-voltage direct-current (HVDC) electric power transmission systems have become viable as technology provided efficient means of changing the voltage of DC power. HVDC systems, however, tend to be more expensive and less efficient over shorter distances than transformers. Transmission with high voltage direct current was not feasible when Edison, Westinghouse and Tesla were designing their power systems, as there was then no economically viable way to change the voltage of DC.

Three-phase electrical generation is very common. The simplest way is to use three separate coils in the generator stator, physically offset by an angle of 120° (one-third of a complete 360° phase) to each other. Three current waveforms are produced that are equal in magnitude and 120° out of phase to each other. If coils are added opposite to these (60° spacing), they generate the same phases with reverse polarity and so can be simply wired together.

In practice, higher "pole orders" are commonly used. For example, a 12-pole machine would have 36 coils (10° spacing). The advantage is that lower rotational speeds can be used to generate the same frequency. For example, a 2-pole machine running at 3600 rpm and a 12-pole machine running at 600 rpm produce the same frequency; the lower speed is preferable for larger machines.

If the load on a three-phase system is balanced equally among the phases, no current flows through the neutral point. Even in the worst-case unbalanced (linear) load, the neutral current will not exceed the highest of the phase currents. Non-linear loads (e.g., the switch-mode power supplies widely used) may require an oversized neutral bus and neutral conductor in the upstream distribution panel to handle harmonics. Harmonics can cause neutral conductor current levels to exceed that of one or all phase conductors.

For three-phase at utilization voltages a four-wire system is often used. When stepping down three-phase, a transformer with a Delta (3-wire) primary and a Star (4-wire, center-earthed) secondary is often used so there is no need for a neutral on the supply side.

For smaller customers (just how small varies by country and age of the installation) only a single phase and neutral, or two phases and neutral, are taken to the property. For larger installations all three phases and neutral are taken to the main distribution panel. From the three-phase main panel, both single and three-phase circuits may lead off.

Three-wire single-phase systems, with a single center-tapped transformer giving two live conductors, is a common distribution scheme for residential and small commercial buildings in North America. This arrangement is sometimes incorrectly referred to as “two phase”. A similar method is used for a different reason on construction sites in the UK. Small power tools and lighting are supposed to be supplied by a local center-tapped transformer with a voltage of 55 V between each power conductor and earth. This significantly reduces the risk of electric shock in the event that one of the live conductors becomes exposed through an equipment fault whilst still allowing a reasonable voltage of 110 V between the two conductors for running the tools.

A third wire, called the bond (or earth) wire, is often connected between non-current-carrying metal enclosures and earth ground. This conductor provides protection from electric shock due to accidental contact of circuit conductors with the metal chassis of portable appliances and tools. Bonding all non-current-carrying metal parts into one complete system ensures there is always a low electrical impedance path to ground sufficient to carry any fault current for as long as it takes for the system to clear the fault. This low impedance path allows the maximum amount of fault current, causing the overcurrent protection device (breakers, fuses) to trip or burn out as quickly as possible, bringing the electrical system to a safe state. All bond wires are bonded to ground at the main service panel, as is the Neutral/Identified conductor if present.

1.6.2 AC power supply frequencies

Further information: Mains electricity by country

The frequency of the electrical system varies by country and sometimes within a country; most electric power is generated at either 50 or 60 hertz. Some countries have a mixture of 50 Hz and 60 Hz supplies, notably electricity power transmission in Japan.

A low frequency eases the design of electric motors, particularly for hoisting, crushing and rolling applications, and commutator-type traction motors for applications such as railways. However, low frequency also causes noticeable flicker in arc lamps and incandescent light bulbs. The use of lower frequencies also provided the advantage of lower impedance losses, which are proportional to frequency. The original Niagara Falls generators were built to produce 25 Hz power, as a compromise between low frequency for traction and heavy induction motors, while still allowing incandescent lighting to operate (although with noticeable flicker). Most of the 25 Hz residential and commercial customers for Niagara Falls power were converted to 60 Hz by the late 1950s, although some 25 Hz industrial customers still existed as of the start of the 21st century. 16.7 Hz power (formerly 16 2/3 Hz) is still used in some European rail systems, such as in Austria, Germany, Norway, Sweden and Switzerland.

Off-shore, military, textile industry, marine, aircraft, and spacecraft applications sometimes use 400 Hz, for benefits of reduced weight of apparatus or higher motor speeds.

Computer mainframe systems are often powered by 415 Hz, using customer-supplied 35 or 70 KVA motor-generator sets.[3] Smaller mainframes may have an internal 415 Hz M-G set. In any case, the input to the M-G set is the local customary voltage and frequency, variously 200 (Japan), 208, 240 (North America), 380, 400 or 415 (Europe) volts, and variously 50 or 60 Hz.

1.6.3 Effects at high frequencies

Main article: Skin effect

A direct current flows uniformly throughout the cross-section of a uniform wire. An alternating current of any frequency is forced away from the wire’s center, toward its outer surface. This is because the acceleration of an electric charge in an alternating current produces waves of electromagnetic radiation that cancel the propagation of electricity toward the center of materials with high conductivity. This phenomenon is called skin effect.

At very high frequencies the current no longer flows *in* the wire, but effectively flows *on* the surface of the wire, within a thickness of a few skin depths. The skin depth is the thickness at which the current density is reduced by 63%. Even at relatively low frequencies used for power transmission (50–60 Hz), non-uniform distribution of current still occurs in sufficiently thick conductors. For example, the skin depth of a copper conductor is approximately 8.57 mm at 60 Hz, so high current conductors are usually hollow to reduce their mass and cost.

Since the current tends to flow in the periphery of conductors, the effective cross-section of the conductor is reduced. This increases the effective AC resistance of the conductor, since resistance is inversely proportional to the cross-sectional area. The AC resistance often is many times higher than the DC resistance, causing a much higher energy loss due to ohmic heating (also called I^2R loss).

Techniques for reducing AC resistance

For low to medium frequencies, conductors can be divided into stranded wires, each insulated from one other, and the relative positions of individual strands specially arranged within the conductor bundle. Wire constructed using this technique is called Litz wire. This measure helps to partially mitigate skin effect by forcing more equal current throughout the total cross section of the stranded conductors. Litz wire is used for making high-Q inductors, reducing losses in flexible conductors carrying very high currents at lower frequencies, and in the windings of devices carrying higher radio frequency current (up to hundreds of kilohertz), such as switch-mode power supplies and radio frequency transformers.

Techniques for reducing radiation loss As written above, an alternating current is made of electric charge under periodic acceleration, which causes radiation of electromagnetic waves. Energy that is radiated is lost. Depending on the frequency, different techniques are used to minimize the loss due to radiation.

Twisted pairs At frequencies up to about 1 GHz, pairs of wires are twisted together in a cable, forming a twisted pair. This reduces losses from electromagnetic radiation and inductive coupling. A twisted pair must be used with a balanced signalling system, so that the two wires carry equal but opposite currents. Each wire in a twisted pair radiates a signal, but it is effectively cancelled by radiation from the other wire, resulting in almost no radiation loss.

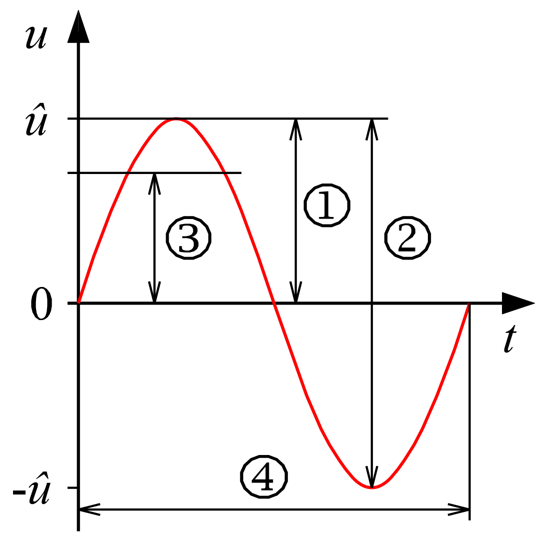
Coaxial cables Coaxial cables are commonly used at audio frequencies and above for convenience. A coaxial cable has a conductive wire inside a conductive tube, separated by a dielectric layer. The current flowing on the inner conductor is equal and opposite to the current flowing on the inner surface of the tube. The electromagnetic field is thus completely contained within the tube, and (ideally) no energy is lost to radiation or coupling outside the tube. Coaxial cables have acceptably small losses for frequencies up to about 5 GHz. For microwave frequencies greater than 5 GHz, the losses (due mainly to the electrical resistance of the central conductor) become too large, making waveguides a more efficient medium for transmitting energy. Coaxial cables with an air rather than solid dielectric are preferred as they transmit power with lower loss.

Waveguides Waveguides are similar to coax cables, as both consist of tubes, with the biggest difference being that the waveguide has no inner conductor. Waveguides can have any arbitrary cross section, but rectangular cross sections are the most common. Because waveguides do not have an inner conductor to carry a return current, waveguides cannot deliver energy by means of an electric current, but rather by means of a *guided* electromagnetic field. Although surface currents do flow on the inner walls of the waveguides, those surface currents do not carry power. Power is carried by the guided electromagnetic fields. The surface currents are set up by the guided electromagnetic fields and have the effect of keeping the fields inside the waveguide and preventing leakage of the fields to the space outside the waveguide.

Waveguides have dimensions comparable to the wavelength of the alternating current to be transmitted, so they are only feasible at microwave frequencies. In addition to this mechanical feasibility, electrical resistance of the non-ideal metals forming the walls of the waveguide cause dissipation of power (surface currents flowing on lossy conductors dissipate power). At higher frequencies, the power lost to this dissipation becomes unacceptably large.

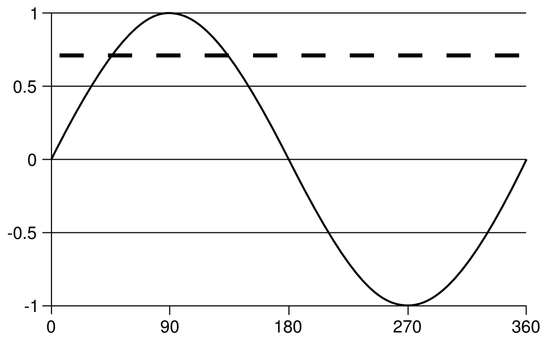
Fiber optics At frequencies greater than 200 GHz, waveguide dimensions become impractically small, and the ohmic losses in the waveguide walls become large. Instead, fiber optics, which are a form of dielectric waveguides, can be used. For such frequencies, the concepts of voltages and currents are no longer used.

1.6.4 Mathematics of AC voltages



A sinusoidal alternating voltage.
1 = peak, also amplitude,
2 = peak-to-peak,
3 = effective value,
4 = Period

Alternating currents are accompanied (or caused) by alternating voltages. An AC voltage v can be described mathematically as a function of time by the following equation:



A sine wave, over one cycle (360°). The dashed line represents the root mean square (RMS) value at about 0.707

$v(t) = V_{\text{peak}} \cdot \sin(\omega t)$

where

- V_{peak} is the peak voltage (unit: volt),
- ω is the angular frequency (unit: radians per second)
    - The angular frequency is related to the physical frequency, f (unit = hertz), which represents the number of cycles per second, by the equation $\omega = 2\pi f$.
- t is the time (unit: second).

The peak-to-peak value of an AC voltage is defined as the difference between its positive peak and its negative peak. Since the maximum value of $\sin(x)$ is +1 and the minimum value is −1, an AC voltage swings between $+V_{\text{peak}}$ and $-V_{\text{peak}}$. The peak-to-peak voltage, usually written as V_{pp} or $V_{\text{P-P}}$, is therefore $V_{\text{peak}} - (-V_{\text{peak}}) = 2V_{\text{peak}}$.

Power

Main article: AC power

The relationship between voltage and the power delivered is

$p(t) = \frac{v^2(t)}{R}$ where R represents a load resistance.

Rather than using instantaneous power, $p(t)$, it is more practical to use a time averaged power (where the averaging is performed over any integer number of cycles). Therefore, AC voltage is often expressed as a root mean square (RMS) value, written as V_{rms} , because

$$P_{\text{time averaged}} = \frac{{V^2}_{\text{rms}}}{R}.$$

Power oscillation $v(t) = V_{\text{peak}} \sin(\omega t)$

$i(t) = \frac{v(t)}{R} = \frac{V_{\text{peak}}}{R} \sin(\omega t)$

$P(t) = v(t)\, i(t) = \frac{(V_{\text{peak}})^2}{R} \sin^2(\omega t)$

By the following trigonometric identity, the power oscillation is double frequency of the voltage.

$$\sin^2 x = \frac{1 - \cos 2x}{2}$$

Root mean square voltage

Further information: RMS amplitude
For a broader coverage related to this topic, see Root mean square voltage.

Below it is assumed an AC waveform (with no DC component).

- For a sinusoidal voltage:

$$\begin{aligned} V_{\text{rms}} &= \sqrt{\frac{1}{T}\int_0^T [V_{pk}\sin(\omega t + \phi)]^2 dt} \\ &= V_{pk}\sqrt{\frac{1}{2T}\int_0^T [1 - \cos(2\omega t + 2\phi)] dt} \\ &= V_{pk}\sqrt{\frac{1}{2T}\int_0^T dt} \\ &= \frac{V_{pk}}{\sqrt{2}} \end{aligned}$$

The factor $\sqrt{2}$ is called the crest factor, which varies for different waveforms.

- For a triangle waveform centered about zero

$$V_{\text{rms}} = \frac{V_{\text{peak}}}{\sqrt{3}}.$$

- For a square waveform centered about zero

$$V_{\text{rms}} = V_{\text{peak}}.$$

- For an arbitrary periodic waveform $v(t)$ of period T :

$$V_{\text{rms}} = \sqrt{\frac{1}{T}\int_0^T [v(t)]^2 dt}.$$

Example

To illustrate these concepts, consider a 230 V AC mains supply used in many countries around the world. It is so called because its root mean square value is 230 V. This means that the time-averaged power delivered is equivalent to the power delivered by a DC voltage of 230 V. To determine the peak voltage (amplitude), we can rearrange the above equation to:

$$V_{\text{peak}} = \sqrt{2}\, V_{\text{rms}}.$$

For 230 V AC, the peak voltage V_{peak} is therefore $230V \times \sqrt{2}$, which is about 325 V.

1.6.5 Information transmission

Alternating current is used to transmit information, as in the cases of telephone and cable television. Information signals are carried over a wide range of AC frequencies. POTS telephone signals have a frequency of about 3 kilohertz, close to the baseband audio frequency. Cable television and other cable-transmitted information currents may alternate at frequencies of tens to thousands of megahertz. These frequencies are similar to the electromagnetic wave frequencies often used to transmit the same types of information over the air.

1.6.6 History

The first alternator to produce alternating current was a dynamo electric generator based on Michael Faraday's principles constructed by the French instrument maker Hippolyte Pixii in 1832.[4] Pixii later added a commutator to his device to produce the (then) more commonly used direct current. The earliest recorded practical application of alternating current is by Guillaume Duchenne, inventor and developer of electrotherapy. In 1855, he announced that AC was superior to direct current for electrotherapeutic triggering of muscle contractions.[5]

Alternating current technology had first developed in Europe due to the work of Guillaume Duchenne (1850s), The Hungarian Ganz Works (1870s), Sebastian Ziani de Ferranti (1880s), Lucien Gaulard, and Galileo Ferraris.

In 1876, Russian engineer Pavel Yablochkov invented a lighting system based on a set of induction coils where the primary windings were connected to a source of AC. The secondary windings could be connected to several 'electric candles' (arc lamps) of his own design.[6][7] The coils Yablochkov employed functioned essentially as transformers.[6]

In 1878, the Ganz factory, Budapest, Hungary, began manufacturing equipment for electric lighting and, by 1883, had installed over fifty systems in Austria-Hungary. Their AC systems used arc and incandescent lamps, generators, and other equipment.[8]

A power transformer developed by Lucien Gaulard and John Dixon Gibbs was demonstrated in London in 1881, and attracted the interest of Westinghouse. They also exhibited the invention in Turin in 1884.

DC distribution systems

During the initial years of electricity distribution, Edison's direct current was the standard for the United States, and Edison did not want to lose all his patent royalties.[9] Direct current worked well with incandescent lamps, which were the principal load of the day, and with motors. Direct-current systems could be directly used with storage batteries, providing valuable load-leveling and backup power during interruptions of generator operation. Direct-current generators could be easily paralleled, allowing economical operation by using smaller machines during periods of light load and improving reliability. At the introduction of Edison's system, no practical AC motor was available. Edison had invented a meter to allow customers to be billed for energy proportional to consumption, but this meter worked only with direct current.

The principal drawback of direct-current distribution was that customer loads, distribution and generation were all at the same voltage. Generally, it was uneconomical to use a high voltage for transmission and reduce it for customer uses. Even with the Edison 3-wire system (placing two 110-volt customer loads in series on a 220-volt supply), the high cost of conductors required generation to be close to customer loads, otherwise losses made the system uneconomical to operate.

Transformers

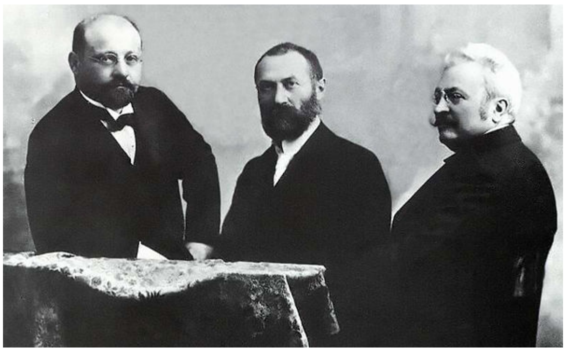
Alternating current systems can use transformers to change voltage from low to high level and back, allowing generation and consumption at low voltages but transmission, possibly over great distances, at high voltage, with savings in the cost of conductors and energy losses.

A bipolar open-core power transformer developed by Lucien Gaulard and John Dixon Gibbs was demonstrated in London in 1881, and attracted the interest of Westinghouse. They also exhibited the invention in Turin in 1884. However these early induction coils with open magnetic circuits are inefficient at transferring power to loads. Until about 1880, the paradigm for AC power transmission from a high voltage supply to a low voltage load was a series circuit. Open-core transformers with a ratio near 1:1 were connected with their primaries in series to allow use of a high voltage for transmission while presenting a low voltage to the lamps. The inherent flaw in this method was that turning off a single lamp (or other electric device) affected the voltage supplied to all others on the same circuit. Many adjustable transformer designs

were introduced to compensate for this problematic characteristic of the series circuit, including those employing methods of adjusting the core or bypassing the magnetic flux around part of a coil.[10]
The direct current systems did not have these drawbacks, giving it significant advantages over early AC systems.

Pioneers

The prototype of ZBD. transformer is on display at the Széchenyi István Memorial Exhibition, Nagycenk, Hungary



The Hungarian "ZBD" Team (Károly Zipernowsky, Ottó Bláthy, Miksa Déri). They were the inventors of the first high efficiency, closed core shunt connection transformer. The three also invented the modern power distribution system: Instead of former series connection they connect transformers that supply the appliances in parallel to the main line.Blathy invented the AC Wattmeter, and they invented the essential Constant Voltage Generator.

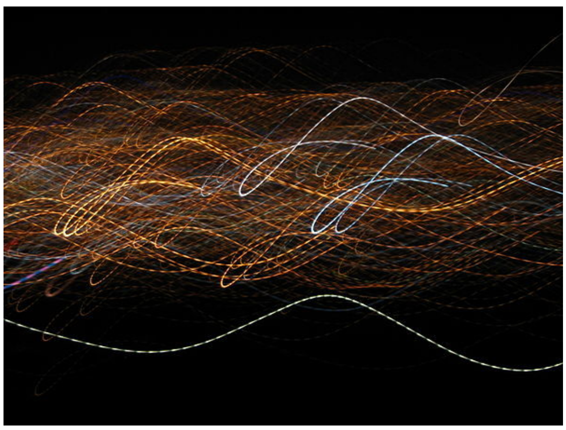
In the autumn of 1884, Károly Zipernowsky, Ottó Bláthy and Miksa Déri (ZBD), three engineers associated with the Ganz factory, determined that open-core devices were impractical, as they were incapable of reliably regulating voltage.[11] In their joint 1885 patent applications for novel transformers (later called ZBD transformers), they described two designs with closed magnetic circuits where copper windings were either a) wound around iron wire ring core or b) surrounded by iron wire core.[10] In both designs, the magnetic flux linking the primary and secondary windings traveled almost entirely within the confines of the iron core, with no intentional path through air (see Toroidal cores below). The new transformers were 3.4 times more efficient than the open-core bipolar devices of Gaulard and Gibbs.[12]

The Ganz factory in 1884 shipped the world's first five high-efficiency AC transformers.[13] This first unit had been manufactured to the following specifications: 1,400 W, 40 Hz, 120:72 V, 11.6:19.4 A, ratio 1.67:1, one-phase, shell form.[13]

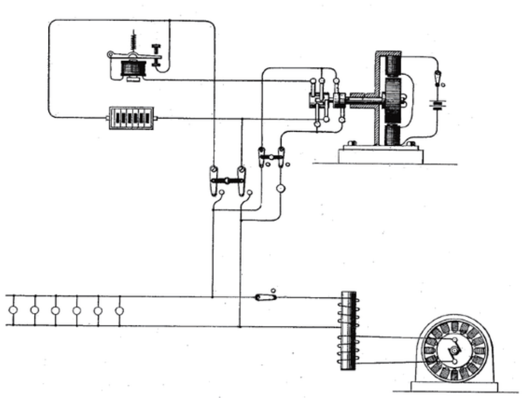
The ZBD patents included two other major interrelated innovations: one concerning the use of parallel connected, instead of series connected, utilization loads, the other concerning the ability to have high turns ratio transformers such that the supply network voltage could be much higher (initially 1,400 to 2,000 V) than the voltage of utilization loads (100 V initially preferred).[14][15] When employed in parallel connected electric distribution systems, closed-core transformers finally made it technically and economically feasible to provide electric power for lighting in homes, businesses and public spaces.[16][17]

The other essential milestone was the introduction of 'voltage source, voltage intensive' (VSVI) systems'[18] by the invention of constant voltage generators in 1885.[19] Ottó Bláthy also invented the first AC electricity meter.[20][21][22][23]

The AC power systems was developed and adopted rapidly after 1886 due to its ability to distribute electricity efficiently over long distances, overcoming the limitations of the direct current system. In 1886, the ZBD engineers designed, and the Ganz factory supplied electrical equipment for, the world's first power station that used AC generators to power a parallel connected common electrical network, the steam-powered Rome-Cerchi power plant.[24] The reliability of the AC technology received impetus after the Ganz Works electrified a large European metropolis: Rome in 1886.[24]



The city lights of Prince George, British Columbia viewed in a motion blurred exposure. The AC blinking causes the lines to be dotted rather than continuous.



Westinghouse Early AC System 1887
(US patent 373035)

In the UK Sebastian de Ferranti, who had been developing AC generators and transformers in London since 1882, redesigned the AC system at the Grosvenor Gallery power station in 1886 for the London Electric Supply Corporation (LESCo) including alternators of his own design and transformer designs similar to Gaulard and Gibbs.[25] In 1890 he designed their power station at Deptford[26] and converted the Grosvenor Gallery station across the Thames into an electrical substation, showing the way to integrate older plants into a universal AC supply system.[27]

In the US William Stanley, Jr. designed one of the first practical devices to transfer AC power efficiently between isolated circuits. Using pairs of coils wound on a common iron core, his design, called an induction coil, was an early (1885) transformer. Stanley also worked on engineering and adapting European designs such as the Gaulard and Gibbs transformer for US entrepreneur George Westinghouse who started building AC systems in 1886. The spread of Westinghouse and other AC systems triggered a push back in late 1887 by Thomas Edison (a proponent of direct current) who attempted to discredit alternating current as too dangerous in a public campaign called the "War of Currents".

In 1888 alternating current systems gained further viability with introduction of a functional AC motor, something these systems had lacked up till then. The design, an induction motor, was independently invented by Galileo Ferraris and Nikola Tesla (with Tesla's design being licensed by Westinghouse in the US). This design was further developed into the modern practical three-phase form by Mikhail Dolivo-Dobrovolsky and Charles Eugene Lancelot Brown.[28]

The Ames Hydroelectric Generating Plant (spring of 1891) and the original Niagara Falls Adams Power Plant (August 25, 1895) were among the first hydroelectric AC-power plants. The first commercial power plant in the United States using three-phase alternating current was the hydroelectric Mill Creek No. 1 Hydroelectric Plant near Redlands, California, in 1893 designed by Almirian Decker. Decker's design incorporated 10,000-volt three-phase transmission and established the standards for the complete system of generation, transmission and motors used today.

The Jaruga Hydroelectric Power Plant in Croatia was set in operation on 28 August 1895. The two generators (42 Hz, 550 kW each) and the transformers were produced and installed by the Hungarian company Ganz. The transmission line from the power plant to the City of Šibenik was 11.5 kilometers (7.1 mi) long on wooden towers, and the municipal distribution grid 3000 V/110 V included six transforming stations.

Alternating current circuit theory developed rapidly in the latter part of the 19th and early 20th century. Notable contributors to the theoretical basis of alternating current calculations include Charles Steinmetz, Oliver Heaviside, and many others.[29][30] Calculations in unbalanced three-phase systems were simplified by the symmetrical components methods discussed by Charles Legeyt Fortescue in 1918.

1.6.7 See also

- AC power
- Direct current
- Electric current
- Electrical wiring
- Heavy-duty power plugs
- Hertz
- Mains power systems
- AC power plugs and sockets
- Utility frequency
- War of Currents
- AC/DC receiver design

1.6.8 References

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- Professor Mark Csele’s tour of the 25 Hz Rankine generating station
- 50/60 hertz information
- AC circuits Animations and explanations of vector (phasor) representation of RLC circuits
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- (Italian) Generating an AC voltage. Interactive.

Chapter 2

Electrical components

2.1 Active and passive components

Passivity is a property of engineering systems, used in a variety of engineering disciplines, but most commonly found in analog electronics and control systems. A **passive component**, depending on field, may be either a component that consumes (but does not produce) energy (thermodynamic passivity), or a component that is incapable of power gain (incremental passivity).

A component that is not passive is called an **active component**. An electronic circuit consisting entirely of passive components is called a passive circuit (and has the same properties as a passive component). Used out-of-context and without a qualifier, the term **passive** is ambiguous. Typically, analog designers use this term to refer to **incrementally passive** components and systems, while control systems engineers will use this to refer to **thermodynamically passive** ones.

Systems for which the small signal model is not passive are sometimes called locally active (e.g. transistors and tunnel diodes). Systems that can generate power about a time-variant unperturbed state are often called parametrically active (e.g. certain types of nonlinear capacitors).[1]

2.1.1 Thermodynamic passivity

In control systems and circuit network theory, a passive component or circuit is one that consumes energy, but does not produce energy. Under this methodology, voltage and current sources are considered active, while resistors, capacitors, inductors, transistors, tunnel diodes, metamaterials and other dissipative and energy-neutral components are considered passive. Circuit designers will sometimes refer to this class of components as dissipative, or thermodynamically passive.

While many books give definitions for passivity, many of these contain subtle errors in how initial conditions are treated (and, occasionally, the definitions do not generalize to all types of nonlinear time-varying systems with memory). Below is a correct, formal definition, taken from Wyatt et al.[2] (which also explains the problems with many other definitions). Given an *n*-port *R* with a state representation *S*, and initial state *x*, define available energy *EA* as:

$$E_A(x) = \sup_{x \to T \geq 0} \int_0^T -\langle v(t), i(t) \rangle \, \mathrm{d}t$$

where the notation sup$x \to T \geq_0$ indicates that the supremum is taken over all $T \geq 0$ and all admissible pairs $\{v(\cdot), i(\cdot)\}$ with the fixed initial state *x* (e.g., all voltage–current trajectories for a given initial condition of the system). A system is considered passive if *EA* is finite for all initial states *x*. Otherwise, the system is considered active. Roughly speaking, the inner product $\langle v(t), i(t) \rangle$ is the instantaneous power (e.g., the product of voltage and current), and *EA* is the upper bound on the integral of the instantaneous power (i.e., energy). This upper bound (taken over all $T \geq 0$) is the *available energy* in the system for the particular initial condition *x*. If, for all possible initial states of the system, the energy available is finite, then the system is called *passive.*

2.1.2 Incremental passivity

In circuit design, informally, passive components refer to ones that are not capable of power gain; this means they cannot amplify signals. Under this definition, passive components include capacitors, inductors, resistors, diodes, transformers, voltage sources, and current sources. They exclude devices like transistors, vacuum tubes, relays, tunnel diodes, and glow tubes. Formally, for a memoryless two-terminal element, this means that the current–voltage characteristic is monotonically increasing. For this reason, control systems and circuit network theorists refer to these devices as locally passive, incrementally passive, increasing, monotone increasing, or monotonic. It is not clear how this definition would be formalized to multiport devices with memory – as a practical matter, circuit designers use this term informally, so it may not be necessary to formalize it.[nb 1]

This term is used colloquially in a number of other contexts:

- A passive USB to PS/2 adapter consists of wires, and potentially resistors and similar passive (in both the incremental and thermodynamic sense) components. An active USB to PS/2 adapter consists of logic to translate signals (active in the incremental sense)

- A passive mixer consists of just resistors (incrementally passive), whereas an active mixer includes components capable of gain (active).
- In audio work one can also find both (incrementally) passive and active converters between balanced and unbalanced lines. A passive bal/unbal converter is generally just a transformer along with, of course, the requisite connectors, while an active one typically consists of a differential drive or an instrumentation amplifier.

2.1.3 Other definitions of passivity

In some very informal settings, passivity may refer to the simplicity of the device, although this definition is now almost universally considered incorrect. Here, devices like diodes would be considered active,[3] and only very simple devices like capacitors, inductors, and resistors are considered passive. In some cases, the term "linear element" may be a more appropriate term than “passive device.” In other cases, "solid state device" may be a more appropriate term than “active device.”

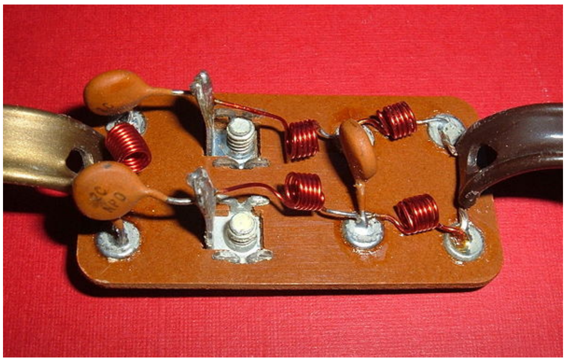
2.1.4 Stability

Passivity, in most cases, can be used to demonstrate that passive circuits will be stable under specific criteria. Note that this only works if only one of the above definitions of passivity is used – if components from the two are mixed, the systems may be unstable under any criteria. In addition, passive circuits will not necessarily be stable under all stability criteria. For instance, a resonant series LC circuit will have unbounded voltage output for a bounded voltage input, but will be stable in the sense of Lyapunov, and given bounded energy input will have bounded energy output.

Passivity is frequently used in control systems to design stable control systems or to show stability in control systems. This is especially important in the design of large, complex control systems (e.g. stability of airplanes). Passivity is also used in some areas of circuit design, especially filter design.

2.1.5 Passive filter

A passive filter is a kind of electronic filter that is made only from passive components – in contrast to an active filter, it does not require an external power source (beyond the signal). Since most filters are linear, in most cases, passive filters are composed of just the four basic linear elements – resistors, capacitors, inductors, and transformers. More complex passive filters may involve nonlinear elements, or more complex linear elements, such as transmission lines.



Television signal splitter consisting of a passive high-pass filter (left) and a passive low-pass filter (right). The antenna is connected to the screw terminals to the left of center.

A passive filter has several advantages over an active filter:

- Guaranteed stability
- Scale better to large signals (tens of amperes, hundreds of volts), where active devices are often impractical
- No power supply needed
- Often less expensive in discrete designs (unless large coils are required)
- For linear filters, potentially greater linearity depending on components required

They are commonly used in speaker crossover design (due to the moderately large voltages and currents, and the lack of easy access to a power supply), filters in power distribution networks (due to the large voltages and currents), power supply bypassing (due to low cost, and in some cases, power requirements), as well as a variety of discrete and home brew circuits (for low-cost and simplicity). Passive filters are uncommon in monolithic integrated circuit design, where active devices are inexpensive compared to resistors and capacitors, and inductors are prohibitively expensive. Passive filters are still found, however, in hybrid integrated circuits. Indeed, it may be the desire to incorporate a passive filter that leads the designer to use the hybrid format.

2.1.6 Notes

[1] This is probably formalized in one of the extensions to Duffin’s Theorem. One of the extensions may state that if the small signal model is thermodynamically passive, under some conditions, the overall system will be incrementally passive, and therefore, stable. This needs to be verified.

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- Chua, Leon; Desoer, Charles; Kuh, Ernest (1987). *Linear and Nonlinear Circuits*. McGraw–Hill Companies. ISBN 0-07-010898-6.—Good collection of passive stability theorems, but restricted to memoryless one-ports. Readable and formal.

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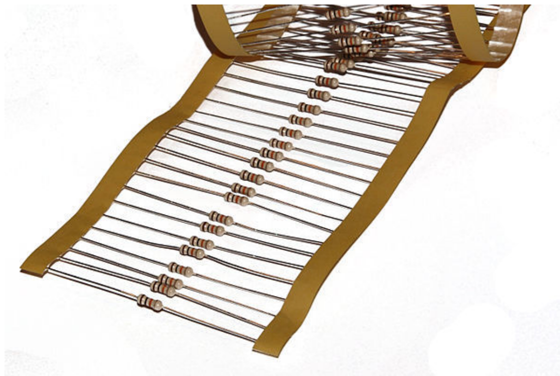
  — A pair of memos that have good discussions of passivity.

2.2 Resistor



Axial-lead resistors on tape. The component is cut from the tape during assembly and the part is inserted into the board.

A **resistor** is a passive two-terminal electrical component that implements electrical resistance as a circuit element. Resistors act to reduce current flow, and, at the same time, act to lower voltage levels within circuits. In electronic circuits, resistors are used to limit current flow, to adjust signal levels, bias active elements, and terminate transmission lines among other uses. High-power resistors, that can dissipate many watts of electrical power as heat, may be used as part of motor controls, in power distribution systems, or as test loads for generators. Fixed resistors have resistances that only change slightly with temperature, time or operating voltage. Variable resistors can be used to adjust circuit elements (such as a volume control or a lamp dimmer), or as sensing devices for heat, light, humidity, force, or chemical activity.

Resistors are common elements of electrical networks and electronic circuits and are ubiquitous in electronic equipment. Practical resistors as discrete components can be composed of various compounds and forms. Resistors are also implemented within integrated circuits.

The electrical function of a resistor is specified by its resistance: common commercial resistors are manufactured over a range of more than nine orders of magnitude. The nominal value of the resistance will fall within a manufacturing tolerance.

2.2.1 Electronic symbols and notation

Main article: Electronic symbol

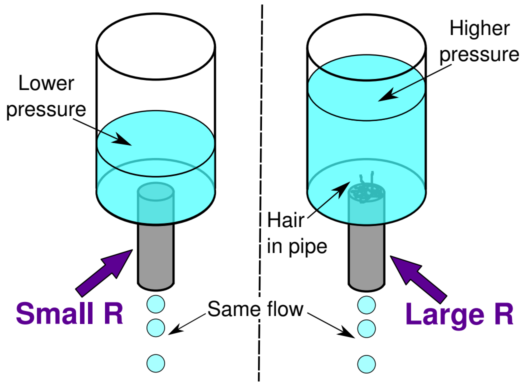
Two typical schematic diagram symbols are as follows:

- (a) resistor, (b) rheostat (variable resistor), and (c) potentiometer

- IEC resistor symbol

The notation to state a resistor's value in a circuit diagram varies. The European notation BS 1852 avoids using a decimal separator, and replaces the decimal separator with the SI prefix symbol for the particular value. For example, *8k2* in a circuit diagram indicates a resistor value of 8.2 kΩ. Additional zeros imply tighter tolerance, for example *15M0*. When the value can be expressed without the need for an SI prefix, an "R" is used instead of the decimal separator. For example, *1R2* indicates 1.2 Ω, and *18R* indicates 18 Ω. The use of a SI prefix symbol or the letter "R" circumvents the problem that decimal separators tend to "disappear" when photocopying a printed circuit diagram.

2.2.2 Theory of operation



The hydraulic analogy compares electric current flowing through circuits to water flowing through pipes. When a pipe (left) is filled with hair (right), it takes a larger pressure to achieve the same flow of water. Pushing electric current through a large resistance is like pushing water through a pipe clogged with hair: It requires a larger push (voltage drop) to drive the same flow (electric current).[1]

Ohm's law

Main article: Ohm's law

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

$$V = I \cdot R.$$

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

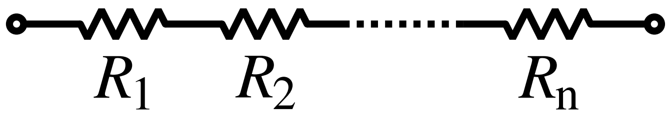
Practical resistors also have some inductance and capacitance which will also affect the relation between voltage and current in alternating current circuits.

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.

Series and parallel resistors

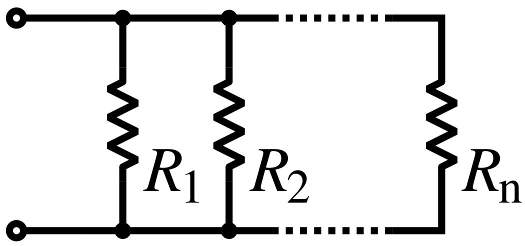
Main article: Series and parallel circuits

The total resistance of resistors connected in series is the sum of their individual resistance values.



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

The total resistance of resistors connected in parallel is the reciprocal of the sum of the reciprocals of the individual resistors.



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

So, for example, a 10 ohm resistor connected in parallel with a 5 ohm resistor and a 15 ohm resistor will produce the inverse of 1/10+1/5+1/15 ohms of resistance, or 1/(.1+.2+.067)=2.725 ohms.

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. Some complex networks of resistors cannot be resolved in this manner, requiring more sophisticated circuit analysis. Generally, the Y-Δ transform, or matrix methods can be used to solve such problems.[2][3][4]

Power dissipation

At any instant, the power P (watts) consumed by a resistor of resistance R (ohms) is calculated as: $P = I^2 R = IV = \frac{V^2}{R}$ where V (volts) is the voltage across the resistor and I (amps) is the current flowing through it. Using Ohm's law, the two other forms can be derived. This power is converted into heat which must be dissipated by the resistor's package before its temperature rises excessively.

Resistors are rated according to their maximum power dissipation. Discrete resistors in solid-state electronic systems are typically rated as 1/10, 1/8, or 1/4 watt. They usually absorb much less than a watt of electrical power and require little attention to their power rating.

An aluminium-housed power resistor rated for 50 W when heat-sinked

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 may not 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.

Since poor air circulation, high altitude, or high operating temperatures may occur, resistors may be specified with higher rated dissipation than will be experienced in service.

All resistors have a maximum voltage rating; this may limit the power dissipation for higher resistance values.

2.2.3 Nonideal properties

Practical resistors have a series inductance and a small parallel capacitance; these specifications can be important in high-frequency applications. In a low-noise amplifier or pre-amp, the noise characteristics of a resistor may be an issue.

The temperature coefficient of the resistance may also be of concern in some precision applications.

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.[5] A family of discrete resistors is also characterized according to its form factor, that is, the size of the device and the position of its leads (or terminals) which is relevant in the practical manufacturing of circuits using them.

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 sinks. In a high-voltage circuit, attention must sometimes be paid to the rated maximum working voltage of the resistor. While there is no minimum working voltage for a given resistor, failure to account for a resistor's maximum rating may cause the resistor to incinerate when current is run through it.

2.2.4 Fixed resistor

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" (pronounced \ˈlēdz\) leaving the body "axially," that is, on a line parallel with the part's longest axis. Others have leads coming off their body "radially" instead. 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

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

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 good 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.[6] These resistors, however, if never subjected to overvoltage nor overheating were remarkably reliable considering the component's size.[7]

Carbon composition resistors are still available, but comparatively quite costly. Values ranged from fractions of an ohm to 22 megohms. Due to their high price, these resistors are no longer used in most applications. However, they are used in power supplies and welding controls.[7]

Carbon pile

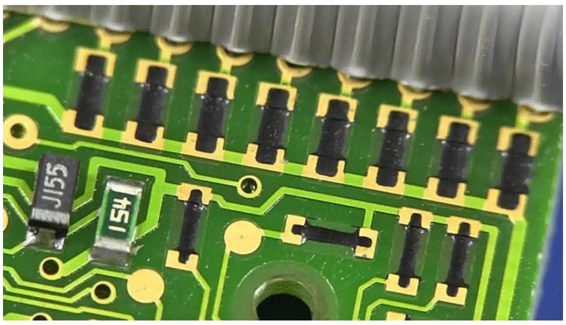
A carbon pile resistor is made of a stack of carbon disks compressed between two metal contact plates. Adjusting the clamping pressure changes the resistance between the plates. These resistors are used when an adjustable load is required, for example in testing automotive batteries or radio transmitters. A carbon pile resistor can also be used as a speed control for small motors in household appliances (sewing machines, hand-held mixers) with ratings up to a few hundred watts.[8] A carbon pile resistor can be incorporated in automatic voltage regulators for generators, where the carbon pile controls the field current to maintain relatively constant voltage.[9] The principle is also applied in the carbon microphone.

Carbon film

Carbon film resistor with exposed carbon spiral (Tesla TR-212 1 kΩ)

A carbon film is deposited on an insulating substrate, and a helix is cut in it to create a long, narrow resistive path. Varying shapes, coupled with the resistivity of amorphous carbon (ranging from 500 to 800 μΩ m), can provide a wide range of resistance values. Compared to carbon composition they feature low noise, because of the precise distribution of the pure graphite without binding.[10] 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.[7]

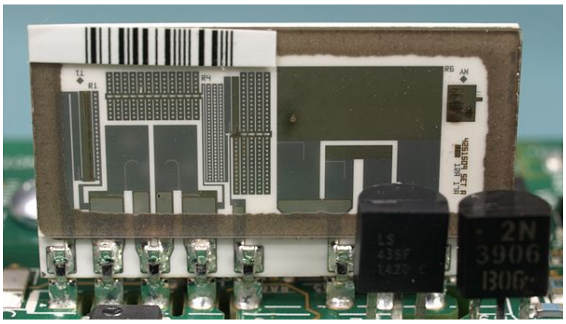
Printed carbon resistor



A carbon resistor printed directly onto the SMD pads on a PCB. Inside a 1989 vintage Psion II Organiser

Carbon composition resistors can be printed directly onto printed circuit board (PCB) substrates as part of the PCB manufacturing process. Although this technique is more common on hybrid PCB modules, it can also be used on standard fibreglass PCBs. Tolerances are typically quite large, and can be in the order of 30%. A typical application would be non-critical pull-up resistors.

Thick and thin film



Laser Trimmed Precision Thin Film Resistor Network from Fluke, used in the Keithley DMM7510 multimeter. Ceramic backed with glass hermetic seal cover.

Thick film resistors became popular during the 1970s, and most SMD (surface mount device) resistors today are of this type. The resistive element of thick films is 1000 times thicker than thin films,[11] but the principal difference is 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.[7]

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 oxide (RuO_2), lead oxide (PbO), bismuth ruthenate ($Bi_2Ru_2O_7$), nickel chromium (NiCr), 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. They also have much lower noise levels, on the level of 10–100 times less than thick film resistors.

Thick film resistors may use the same conductive ceramics, but they are mixed with sintered (powdered) glass and a carrier 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

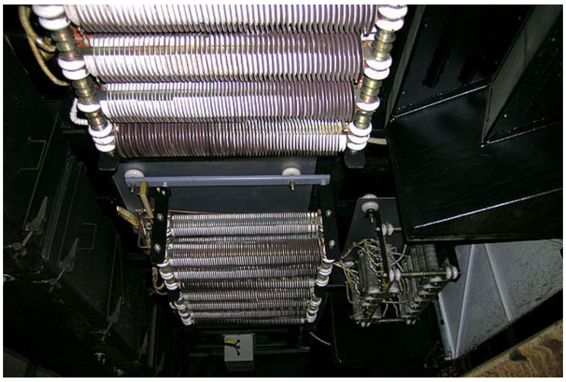
A common type of axial-leaded resistor today is the metal-film resistor. Metal Electrode Leadless Face (MELF) resistors often use the same technology, and are also cylindrically shaped but are designed for surface mounting. Note that other types of resistors (e.g., carbon composition) are also available 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 this is one of the techniques). 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.[12] Metal film resistors possess good noise characteristics and low non-linearity due to a low voltage coefficient. Also beneficial are their tight tolerance, low temperature coefficient and long-term stability.[7]

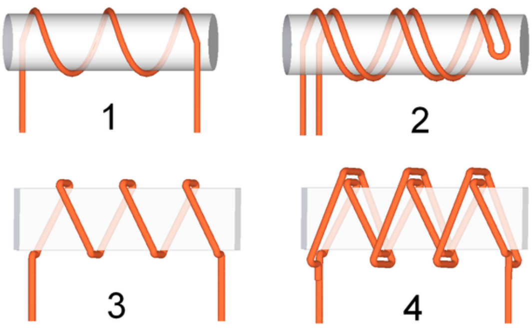
Metal oxide film

Metal-oxide film resistors are made of metal oxides which results in a higher operating temperature and greater stability/reliability than Metal film. They are used in applications with high endurance demands.

Wire wound



High-power wire wound resistors used for dynamic braking on an electric railway car. Such resistors may dissipate many kilowatts for an extended length of time.



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. These resistors are designed to withstand unusually high temperatures of up to 450 °C.[7] 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 – if the outer case is ceramic, such resistors are sometimes described as "cement" resistors, though they do not actually contain any traditional cement. 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 the 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 response of wirewound resistors is substantially worse than that of a composition resistor.[7]

Foil resistor

The primary resistance element of a foil resistor is a special alloy foil several micrometers 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 years) 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.[13]

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 across which the voltage drop is measured and interpreted as current. A typical shunt consists of two solid metal blocks, sometimes brass, mounted on 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 volt meter 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 to 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.[14][15]

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

- Cermet
- Phenolic
- Tantalum
- Water resistor

2.2.5 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.

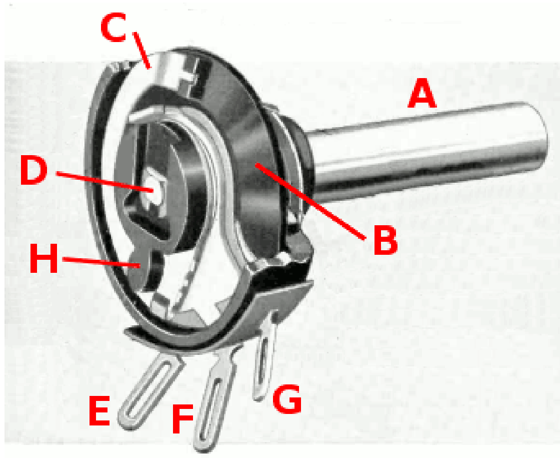
Where continuous adjustment of the resistance value during operation of equipment is required, the sliding resistance tap can be connected to a knob accessible to an operator. Such a device is called a rheostat and has two terminals.

Potentiometers

Main article: Potentiometer

A potentiometer or *pot* is a three-terminal resistor with a continuously adjustable tapping point controlled by rotation of a shaft or knob or by a linear slider.[16] It is called a potentiometer because it can be connected as an adjustable voltage divider to provide a variable potential at the terminal connected to the tapping point. A volume control for an audio device is a common use of a potentiometer. A typical low power potentiometer *(see drawing)* is constructed of a flat resistance element *(B)* of carbon composition, metal film, or conductive plastic, with a springy phosphor bronze wiper contact *(C)* which moves along the surface. An alternate construction is resistance wire wound on a form, with the wiper sliding axially along the coil.[16] These have lower resolution, since as the wiper moves the resistance changes in steps equal to the resistance of a single turn.[16]

Typical panel mount potentiometer



Drawing of potentiometer with case cut away, showing parts: (A) *shaft,* (B) *stationary carbon composition resistance element,* (C) *phosphor bronze wiper,* (D) *shaft attached to wiper,* (E, G) *terminals connected to ends of resistance element,* (F) *terminal connected to wiper.*

An assortment of small through-hole potentiometers designed for mounting on printed circuit boards.

High-resolution multiturn potentiometers are used in a few precision applications. These have wirewound resistance elements typically wound on a helical mandrel, with the wiper moving on a helical track as the control is turned, making continuous contact with the wire. 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, and can typically achieve three digit resolution. 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

Resistance decade box "KURBELWIDERSTAND", made in former East Germany.

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 100 megohms, maximum resolution 0.1 ohm, accuracy 0.1%.[17]

Special devices

There are various devices whose resistance changes with various quantities. The resistance of NTC 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. 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.

2.2.6 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, 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.

2.2.7 Standards

Production resistors

Resistor characteristics are quantified and reported using various national standards. In the US, MIL-STD-202[18] 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 STANDARD CANCELED
- MIL-R-39017 (Fixed, General Purpose, Established Reliability)
- MIL-PRF-32159 (zero ohm jumpers)
- UL 1412 (fusing and temperature limited resistors) [19]

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 106.3 cm 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.[20] 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.[21]

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 charge 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.[22]

2.2.8 Resistor marking

Main article: Electronic color code

Most axial resistors use a pattern of colored stripes to indicate resistance, which also indicate tolerance, and may also be extended to show temperature coefficient and reliability class. Cases are usually tan, brown, blue, or green, though other colors are occasionally found such as dark red or dark gray. The power rating is not usually marked and is deduced from the size.

The color bands of the carbon resistors can be three, four, five or, six bands. The first two bands represent first two digits to measure their value in ohms. The third band of a three- or four-banded resistor represents multiplier; a fourth band denotes tolerance (which if absent, denotes ±20%). For five and six color-banded resistors, the third band is a third digit, fourth band multiplier and fifth is tolerance. The sixth band represents temperature coefficient in a six-banded resistor.

Surface-mount resistors are marked numerically, if they are big enough to permit marking; more-recent small sizes are impractical to mark.

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.

Preferred values

See also: Preferred number § E series

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 geometric 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, by 15, 22, 33, … and preceded by … 0.47, 0.68, 1. This scheme has been adopted as the **E6** series of the IEC 60063 preferred number values. There are also **E12**, **E24**, **E48**, **E96** and **E192** series for components of progressively finer resolution, 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. Manufacturers may sort resistors into tolerance-classes based on measurement. Accordingly, a selection of 100 ohms resistors with a tolerance of ±10%, might not lie just around 100 ohm (but no more than 10% off) as one would expect (a bell-curve), but rather be in two groups – either between 5 to 10% too high or 5 to 10% too low (but not closer to 100 ohm than that) because any resistors the factory had measured as being less than 5% off would have been marked and sold as resistors with only ±5% tolerance or better. When designing a circuit, this may become a consideration. This process of sorting parts based on post-production measurement is known as “binning”, and can be applied to other components than resistors (such as speed grades for CPUs).

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.

SMT resistors

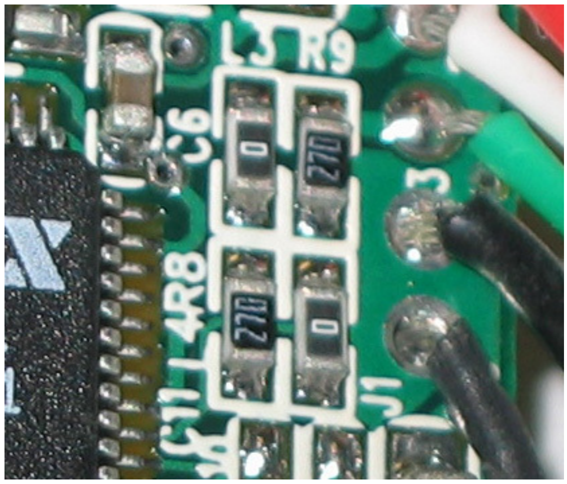
Surface mounted resistors of larger sizes (metric 1608 and above) are printed with numerical values in a code related to that used on axial resistors. Standard-tolerance surface-mount technology (SMT) resistors are marked with a three-digit code, in which the first two digits are the first two significant digits of the value and the third digit is the power of ten (the number of zeroes). For example:

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

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:

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:



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. Their resistance is non-zero but negligible.

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)]* [23]

2.2.9 Electrical and thermal noise

Main article: Noise (electronics)

In amplifying faint signals, it is often necessary to minimize electronic noise, particularly in the first stage of amplification. As a dissipative element, 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 value of resistance produces a larger voltage noise, whereas with a smaller value of resistance there will be more current noise, at a given temperature.

The thermal noise of a practical resistor may also be larger than the theoretical prediction and that increase is typically frequency-dependent. Excess noise of a practical resistor is observed only when 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 are often used 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.[24] Thin film surface mount resistors typically have lower noise and better thermal stability than thick film surface mount resistors. Excess noise is also size-dependent: in general excess noise is reduced as the physical size of a resistor is increased (or multiple resistors are used in parallel), as the independently fluctuating resistances of smaller components will tend to average out.

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 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 to mount the resistors horizontally to avoid temperature gradients and to mind the air flow over the board.[25]

2.2.10 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 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 significant change in its resistance. A safe design generally uses overrated resistors in power applications to avoid this danger.

Low-power thin-film resistors can be damaged by long-term high-voltage stress, even below maximum specified voltage and below maximum power rating. This is often the case for the startup resistors feeding the SMPS integrated circuit.

When overheated, carbon-film resistors may decrease or increase in resistance.[26] 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.

Surface mount resistors have been known to fail due to the ingress of sulfur into the internal makeup of the resistor. This sulfur chemically reacts with the silver layer to produce non-conductive silver sulfide. The resistor's impedance goes to infinity. Sulfur resistant and anti-corrosive resistors are sold into automotive, industrial, and military applications. ASTM B809 is an industry standard that tests a part's susceptibility to sulfur.

An alternative failure mode can be encountered where large value resistors are used (hundreds of kilohms and higher). Resistors are not only specified with a maximum power dissipation, but also for a maximum voltage drop. Exceeding this voltage will cause the resistor to degrade slowly reducing in resistance. The voltage dropped across large value resistors can be exceeded before the power dissipation reaches its limiting value. Since the maximum voltage specified for commonly encountered resistors is a few hundred volts, this is a problem only in applications where these voltages are encountered.

Variable resistors can also 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 indicating the failure of a DC blocking capacitor in the circuit.

2.2.11 See also

- Thermistor
- Piezoresistor
- Circuit design

- Dummy load
- Electrical impedance
- Iron-hydrogen resistor
- Shot noise
- Trimmer (electronics)

2.2.12 References

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2.2.13 External links

- 4-terminal resistors – How ultra-precise resistors work
- Beginner's guide to potentiometers, including description of different tapers
- Color Coded Resistance Calculator – archived with WayBack Machine
- Resistor Types – Does It Matter?
- Standard Resistors & Capacitor Values That Industry Manufactures
- Ask The Applications Engineer – Difference between types of resistors
- Resistors and their uses

2.3 Capacitor

This article is about the electrical component. For the physical phenomenon, see capacitance. For an overview of various kinds of capacitors, see types of capacitor.
"Capacitive" redirects here. For the term used when referring to touchscreens, see capacitive sensing.

A **capacitor** (originally known as a **condenser**) is a passive two-terminal electrical component used to store electrical energy temporarily in an electric field. The forms of practical capacitors vary widely, but all contain at least two electrical conductors (plates) separated by a dielectric (i.e. an insulator that can store energy by becoming polarized). The conductors can be thin films, foils or sintered beads of metal or conductive electrolyte, etc. The nonconducting dielectric acts to increase the capacitor's charge capacity. Materials commonly used as dielectrics include glass, ceramic, plastic film, air, vacuum, paper, mica, and oxide layers. Capacitors are widely used as parts of electrical circuits in many common electrical devices. Unlike a resistor, an ideal capacitor does not dissipate energy. Instead, a capacitor stores energy in the form of an electrostatic field between its plates.

When there is a potential difference across the conductors (e.g., when a capacitor is attached across a battery), an electric field develops across the dielectric, causing positive charge $+Q$ to collect on one plate and negative charge $-Q$ to collect on the other plate. If a battery has been attached to a capacitor for a sufficient amount of time, no current can flow through the capacitor. However, if a time-varying voltage is applied across the leads of the capacitor, a displacement current can flow.

An ideal capacitor is characterized by a single constant value, its capacitance. Capacitance is defined as the ratio of the electric charge Q on each conductor to the potential difference V between them. The SI unit of capacitance is the farad (F), which is equal to one coulomb per volt (1 C/V). Typical capacitance values range from about 1 pF (10^{-12} F) to about 1 mF (10^{-3} F).

The larger the surface area of the "plates" (conductors) and the narrower the gap between them, the greater the capacitance is. In practice, the dielectric between the plates passes a small amount of leakage current and also has an electric field strength limit, known as the breakdown voltage. The conductors and leads introduce an undesired inductance and resistance.

Capacitors are widely used in electronic circuits for blocking direct current while allowing alternating current to pass. In analog filter networks, they smooth the output of power supplies. In resonant circuits they tune radios to particular frequencies. In electric power transmission systems, they stabilize voltage and power flow.[1]

2.3.1 History

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

In October 1745, Ewald Georg von Kleist of Pomerania, Germany, found that charge could be stored by connecting a high-voltage electrostatic generator by a wire to a volume of water in a hand-held glass jar.[2] Von Kleist's hand and the water acted as conductors, and the jar as a dielectric (although details of the mechanism were incorrectly identified at the time). Von Kleist found that touching the wire resulted in a powerful spark, much more painful than that obtained from an electrostatic machine. The following year, the Dutch physicist Pieter van Musschenbroek invented a similar capacitor, which was named the Leyden jar, after the University of Leiden where he worked.[3] He also was impressed by the power of the shock he received, writing, "I would not take a second shock for the kingdom of France."[4]

Daniel Gralath was the first to combine several jars in parallel into a "battery" to increase the charge storage capacity. Benjamin Franklin investigated the Leyden jar and came to the conclusion that the charge was stored on the glass, not in the water as others had assumed. He also adopted the term "battery",[5][6] (denoting the increasing of power with a row of similar units as in a battery of cannon), subsequently applied to clusters of electrochemical cells.[7] Leyden jars were later made by coating the inside and outside of jars with metal foil, leaving a space at the mouth to prevent arcing between the foils. The earliest unit of capacitance was the jar, equivalent to about 1.11 nanofarads.[8]

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

Early capacitors were also known as *condensers*, a term that is still occasionally used today, particularly in high power applications, like automotive systems. The term was first used for this purpose by Alessandro Volta in 1782, with reference to the device's ability to store a higher density of electric charge than a normal isolated conductor.[9]

Since the beginning of the study of electricity non conductive materials like glass, porcelain, paper and mica have been used as insulators. These materials some decades later were also well-suited for further use as the dielectric for the first capacitors. Paper capacitors made by sandwiching a strip of impregnated paper between strips of metal, and rolling the result into a cylinder were commonly used in the late 19century; their manufacture started in 1876,[10] and they were used from the early 20th century as decoupling capacitors in telecommunications (telephony). Porcelain was the precursor in case of all capacitors now belonging to the family of ceramic capacitors. Even in the early years of Marconi`s wireless transmitting apparatus porcelain capacitors were used for high voltage and high frequency application in the transmitters.

On receiver side the smaller mica capacitors were used for resonant circuits. Mica dielectric capacitors were invented in 1909 by William Dubilier. Prior to World War II, mica was the most common dielectric for capacitors in the United States,[10] see Ceramic capacitor#History

Charles Pollak (born Karol Pollak), the inventor of Aluminum electrolytic capacitors, found out that that the oxide layer on an aluminum anode remained stable in a neutral or alkaline electrolyte, even when the power was switched off. In 1896 he filed a patent for an "Electric liquid capacitor with aluminum electrodes" based on his idea of using the oxide layer in a polarized capacitor in combination with a neutral or slightly alkaline electrolyte, see Electrolytic capacitor#History.

With the development of plastic materials by organic chemists during the Second World War, the capacitor industry began to replace paper with thinner polymer films. One very early development in film capacitors was described in British Patent 587,953 in 1944,[10] see Film capacitor#History

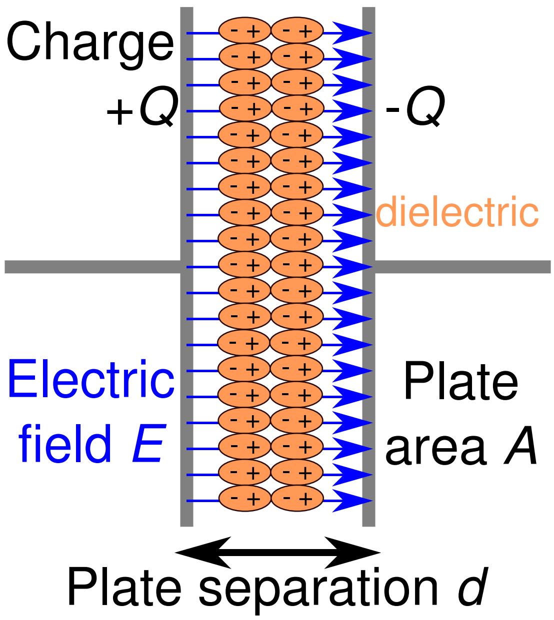
Solid electrolyte tantalum capacitors were invented by Bell Laboratories in the early 1950s as a miniaturized and more reliable low-voltage support capacitor to complement their newly invented transistor, see Tantalum capacitor#History.

Last but not least the electric double-layer capacitor (now Supercapacitors) were invented. In 1957 H. Becker developed a "Low voltage electrolytic capacitor with porous carbon electrodes".[10][11][12] He believed that the energy was stored as a charge in the carbon pores used in his capacitor as in the pores of the etched foils of electrolytic capacitors. Because the double layer mechanism was not known by him at the time, he wrote in the patent: "It is not known exactly what is taking place in the component if it is used for energy storage, but it leads to an extremely high capacity", see Supercapacitor#History.

2.3.2 Theory of operation

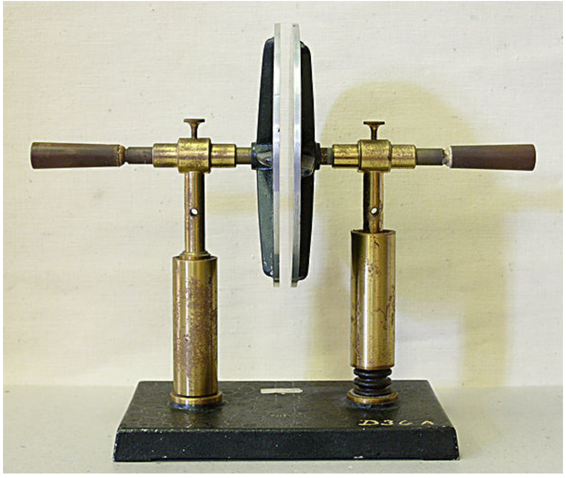
Main article: Capacitance

Overview



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

A capacitor consists of two conductors separated by a non-conductive region.[13] The non-conductive region is called the dielectric. In simpler terms, the dielectric is just an electrical insulator. Examples of dielectric media are glass, air, paper, vacuum, and even a semiconductor depletion region chemically identical to the conductors. A capacitor is assumed to be self-contained and isolated, with no net electric charge and no influence from any external electric field. The conductors thus hold equal and opposite charges on their facing surfaces,[14] and the dielectric develops an electric field. In SI units, a capacitance of one farad means that one coulomb of charge on each conductor causes a voltage of one volt across the device.[15]



A simple demonstration of a parallel-plate capacitor

An ideal capacitor is wholly characterized by a constant capacitance C, defined as the ratio of charge $\pm Q$ on each conductor to the voltage V between them:[13]

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

Because the conductors (or plates) are close together, the opposite charges on the conductors attract one another due to their electric fields, allowing the capacitor to store more charge for a given voltage than if the conductors were separated, giving the capacitor a large capacitance.

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

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

Hydraulic analogy

In the hydraulic analogy, a capacitor is analogous to a rubber membrane sealed inside a pipe. This animation illustrates a membrane being repeatedly stretched and un-stretched by the flow of water, which is analogous to a capacitor being repeatedly charged and discharged by the flow of charge.

In the hydraulic analogy, charge carriers flowing through a wire are analogous to water flowing through a pipe. A capacitor is like a rubber membrane sealed inside a pipe. Water molecules cannot pass through the membrane, but some water can move by stretching the membrane. The analogy clarifies a few aspects of capacitors:

- *The current alters the charge on a capacitor*, just as the flow of water changes the position of the membrane. More specifically, the effect of an electric current is to increase the charge of one plate of the capacitor, and decrease the charge of the other plate by an equal amount. This is just as when water flow moves the rubber membrane, it increases the amount of water on one side of the membrane, and decreases the amount of water on the other side.
- *The more a capacitor is charged, the larger its voltage drop*; i.e., the more it "pushes back" against the charging current. This is analogous to the fact that the more a membrane is stretched, the more it pushes back on the water.
- *Charge can flow "through" a capacitor even though no individual electron can get from one side to the other.* This is analogous to the fact that water can flow through the pipe even though no water molecule can pass through the rubber membrane. Of course, the flow cannot continue in the same direction forever; the capacitor will experience dielectric breakdown, and analogously the membrane will eventually break.
- The *capacitance* describes how much charge can be stored on one plate of a capacitor for a given "push" (voltage drop). A very stretchy, flexible membrane corresponds to a higher capacitance than a stiff membrane.
- A charged-up capacitor is storing potential energy, analogously to a stretched membrane.

Energy of electric field

Work must be done by an external influence to "move" charge between the conductors in a capacitor. When the external influence is removed, the charge separation persists in the electric field and energy is stored to be released when the charge is allowed to return to its equilibrium position. The work done in establishing the electric field, and hence the amount of energy stored, is[16]

$$W = \int_0^Q V(q)\mathrm{d}q = \int_0^Q \frac{q}{C}\mathrm{d}q = \frac{1}{2}\frac{Q^2}{C} = \frac{1}{2}CV^2 = \frac{1}{2}VQ$$

Here Q is the charge stored in the capacitor, V is the voltage across the capacitor, and C is the capacitance.

In the case of a fluctuating voltage $V(t)$, the stored energy also fluctuates and hence power must flow into or out of the capacitor. This power can be found by taking the time derivative of the stored energy:

$$P = \frac{\mathrm{d}W}{\mathrm{d}t} = \frac{\mathrm{d}}{\mathrm{d}t}\left(\frac{1}{2}CV^2\right) = CV(t)\frac{\mathrm{d}V(t)}{\mathrm{d}t}$$

Current–voltage relation

The current $I(t)$ through any component in an electric circuit is defined as the rate of flow of a charge $Q(t)$ passing through it, but actual charges—electrons—cannot pass through the dielectric layer of a capacitor. Rather, one electron accumulates on the negative plate for each one that leaves the positive plate, resulting in an electron depletion and consequent positive charge on one electrode that is equal and opposite to the accumulated negative charge on the other. Thus the charge on the electrodes is equal to the integral of the current as well as proportional to the voltage, as discussed above. As with any antiderivative, a constant of integration is added to represent the initial voltage $V(t_0)$. This is the integral form of the capacitor equation:[17]

$$V(t) = \frac{Q(t)}{C} = \frac{1}{C}\int_{t_0}^{t} I(\tau)\mathrm{d}\tau + V(t_0)$$

Taking the derivative of this and multiplying by C yields the derivative form:[18]

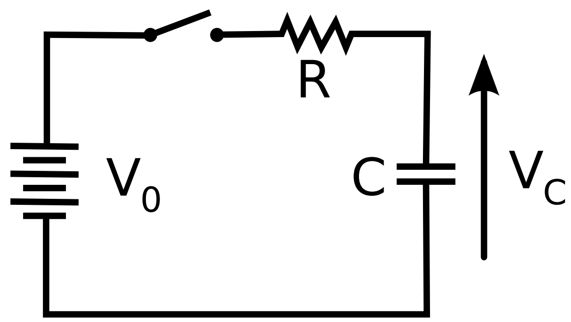
$$I(t) = \frac{\mathrm{d}Q(t)}{\mathrm{d}t} = C\frac{\mathrm{d}V(t)}{\mathrm{d}t}$$

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

DC circuits

See also: RC circuit

A series circuit containing only a resistor, a capacitor, a switch and a constant DC source of voltage V_0 is known as a *charging circuit*.[19] If the capacitor is initially uncharged while the switch is open, and the switch is closed at t_0, it follows from Kirchhoff's voltage law that



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

$$V_0 = v_{\text{resistor}}(t) + v_{\text{capacitor}}(t) = i(t)R + \frac{1}{C}\int_{t_0}^{t} i(\tau)\mathrm{d}\tau$$

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

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

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

$$I(t) = \frac{V_0}{R}e^{-\frac{t}{\tau_0}}$$
$$V(t) = V_0\left(1 - e^{-\frac{t}{\tau_0}}\right)$$

where $\tau_0 = RC$ is the *time constant* of the system. As the capacitor reaches equilibrium with the source voltage, the voltages across the resistor and the current through the entire circuit decay exponentially. The case of *discharging* a charged capacitor likewise demonstrates exponential decay, but with the initial capacitor voltage replacing V_0 and the final voltage being zero.

AC circuits

See also: reactance (electronics) and electrical impedance § Deriving the device-specific impedances

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

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

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

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

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

A capacitor connected to a sinusoidal voltage source will cause a displacement current to flow through it. In the case that the voltage source is $V_0\cos(\omega t)$, the displacement current can be expressed as:

$$I = C\frac{dV}{dt} = -\omega C V_0 \sin(\omega t)$$

At $\sin(\omega t) = -1$, the capacitor has a maximum (or peak) current whereby $I_0 = \omega C V_0$. The ratio of peak voltage to peak current is due to capacitive reactance (denoted XC).

$X_C = \frac{V_0}{I_0} = \frac{V_0}{\omega C V_0} = \frac{1}{\omega C}$

XC approaches zero as ω approaches infinity. If XC approaches 0, the capacitor resembles a short wire that strongly passes current at high frequencies. XC approaches infinity as ω approaches zero. If XC approaches infinity, the capacitor resembles an open circuit that poorly passes low frequencies.

The current of the capacitor may be expressed in the form of cosines to better compare with the voltage of the source:

$$I = -I_0 \sin(\omega t) = I_0 \cos(\omega t + 90^\circ)$$

In this situation, the current is out of phase with the voltage by +π/2 radians or +90 degrees (i.e., the current will lead the voltage by 90°).

Laplace circuit analysis (s-domain)

When using the Laplace transform in circuit analysis, the impedance of an ideal capacitor with no initial charge is represented in the *s* domain by:

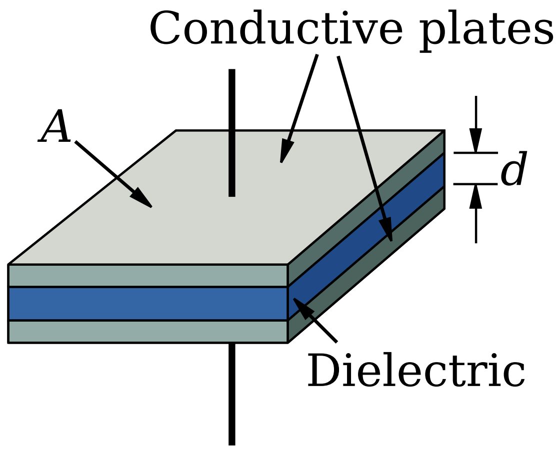
$$Z(s) = \frac{1}{sC}$$

where

- C is the capacitance, and
- s is the complex frequency.

Parallel-plate model

The simplest model capacitor consists of two thin parallel conductive plates separated by a dielectric with permittivity ε . This model may also be used to make



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

qualitative predictions for other device geometries. The plates are considered to extend uniformly over an area A and a charge density $\pm\rho = \pm Q/A$ exists on their surface. Assuming that the length and width of the plates are much greater than their separation d, the electric field near the centre of the device will be uniform with the magnitude $E = \rho/\varepsilon$. The voltage is defined as the line integral of the electric field between the plates

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

Solving this for $C = Q/V$ reveals that capacitance increases with area of the plates, and decreases as separation between plates increases.

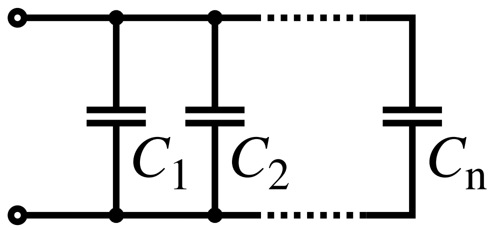
$$C = \frac{\varepsilon A}{d}$$

The capacitance is therefore greatest in devices made from materials with a high permittivity, large plate area, and small distance between plates.

A parallel plate capacitor can only store a finite amount of energy before dielectric breakdown occurs. The capacitor's dielectric material has a dielectric strength U_d which sets the capacitor's breakdown voltage at $V = V_\mathrm{bd} = U_\mathrm{d}d$. The maximum energy that the capacitor can store is therefore

$$E = \frac{1}{2}CV^2 = \frac{1}{2}\frac{\varepsilon A}{d}(U_d d)^2 = \frac{1}{2}\varepsilon A d U_d^2$$

The maximum energy is a function of dielectric volume, permittivity, and dielectric strength. Changing the plate area and the separation between the plates while maintaining the same volume causes no change of the maximum amount of energy that the capacitor can store, so long as the distance between plates remains much smaller than both the length and width of the plates. In addition, these equations assume that the electric field is entirely concentrated in the dielectric between the plates. In reality there are fringing fields outside the dielectric, for example between the sides of the capacitor plates, which will increase the effective capacitance of the capacitor. This is sometimes called parasitic capacitance. For some simple capacitor geometries this additional capacitance term can be calculated analytically.[20] It becomes negligibly small when the ratios of plate width to separation and length to separation are large.



Several capacitors in parallel

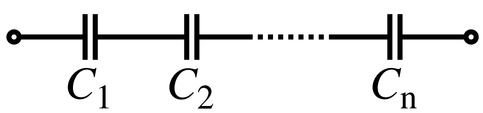
Networks

See also: Series and parallel circuits

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

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

For capacitors in series



Several capacitors in series

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

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

Capacitors are combined in series to achieve a higher working voltage, for example for smoothing a high voltage power supply. The voltage ratings, which are based on plate separation, add up, if capacitance and leakage currents for each capacitor are identical. In such an application, on occasion, series strings are connected in parallel, forming a matrix. The goal is to maximize the energy storage of the network without overloading any capacitor. For high-energy storage with capacitors in series, some safety considerations must be applied to ensure one capacitor failing and leaking current will not apply too much voltage to the other series capacitors.

Series connection is also sometimes used to adapt polarized electrolytic capacitors for bipolar AC use. See electrolytic capacitor#Designing for reverse bias.

Voltage distribution in parallel-to-series networks. To model the distribution of voltages from a single charged capacitor (A) connected in parallel to a chain of capacitors in series (B_{n}) :

$$\begin{aligned}(volts)A_{\text{eq}} &= A\left(1 - \frac{1}{n+1}\right)\\ (volts)B_{1..\text{n}} &= \frac{A}{n}\left(1 - \frac{1}{n+1}\right)\\ A - B &= 0\end{aligned}$$

Note: This is only correct if all capacitance values are equal.

The power transferred in this arrangement is:

$$P = \frac{1}{R} \cdot \frac{1}{n+1} A_{\text{volts}} \left(A_{\text{farads}} + B_{\text{farads}}\right)$$

2.3.3 Non-ideal behavior

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

Breakdown voltage

Main article: Breakdown voltage

Above a particular electric field, known as the dielectric strength *Eds*, the dielectric in a capacitor becomes conductive. The voltage at which this occurs is called the breakdown voltage of the device, and is given by the product of the dielectric strength and the separation between the conductors,[21]

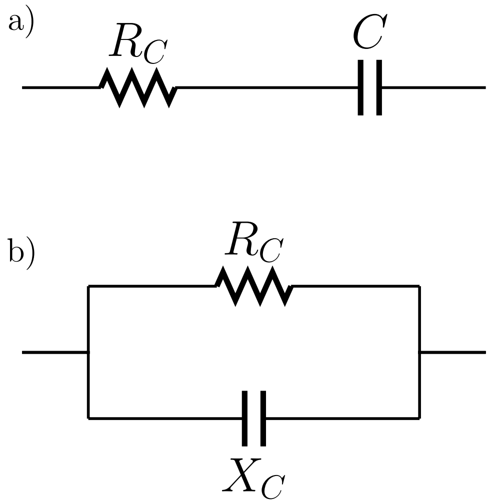
$$V_{\text{bd}} = E_{\text{ds}}d$$

The maximum energy that can be stored safely in a capacitor is limited by the breakdown voltage. Due to the scaling of capacitance and breakdown voltage with dielectric thickness, all capacitors made with a particular dielectric have approximately equal maximum energy density, to the extent that the dielectric dominates their volume.[22]

For air dielectric capacitors the breakdown field strength is of the order 2 to 5 MV/m; for mica the breakdown is 100 to 300 MV/m; for oil, 15 to 25 MV/m; it can be much less when other materials are used for the dielectric.[23] The dielectric is used in very thin layers and so absolute breakdown voltage of capacitors is limited. Typical ratings for capacitors used for general electronics applications range from a few volts to 1 kV. As the voltage increases, the dielectric must be thicker, making high-voltage capacitors larger per capacitance than those rated for lower voltages. The breakdown voltage is critically affected by factors such as the geometry of the capacitor conductive parts; sharp edges or points increase the electric field strength at that point and can lead to a local breakdown. Once this starts to happen, the breakdown quickly tracks through the dielectric until it reaches the opposite plate, leaving carbon behind and causing a short (or relatively low resistance) circuit. The results can be explosive as the short in the capacitor draws current from the surrounding circuitry and dissipates the energy.[24]

The usual breakdown route is that the field strength becomes large enough to pull electrons in the dielectric from their atoms thus causing conduction. Other scenarios are possible, such as impurities in the dielectric, and, if the dielectric is of a crystalline nature, imperfections in the crystal structure can result in an avalanche breakdown as seen in semi-conductor devices. Breakdown voltage is also affected by pressure, humidity and temperature.[25]

Equivalent circuit



Two different circuit models of a real capacitor

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

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

As frequency approaches infinity, the capacitive impedance (or reactance) approaches zero and the ESR becomes significant. As the reactance becomes negligible, power dissipation approaches *P*RMS = *V*RMS^2 /*R*ESR.

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

If the conductors are separated by a material with a small conductivity rather than a perfect dielectric, then a small leakage current flows directly between them. The capacitor therefore has a finite parallel resistance,[15] and slowly discharges over time (time may vary greatly depending on the capacitor material and quality).

Q factor

The quality factor (or Q) of a capacitor is the ratio of its reactance to its resistance at a given frequency, and is a measure of its efficiency. The higher the Q factor of the capacitor, the closer it approaches the behavior of an ideal, lossless, capacitor.

The Q factor of a capacitor can be found through the following formula:

$$Q = \frac{X_C}{R_C} = \frac{1}{\omega C R_C},$$

where ω is angular frequency, C is the capacitance, X_C is the capacitive reactance, and R_C is the series resistance of the capacitor.

Ripple current

Ripple current is the AC component of an applied source (often a switched-mode power supply) whose frequency may be constant or varying. Ripple current causes heat to be generated within the capacitor due to the dielectric losses caused by the changing field strength together with the current flow across the slightly resistive supply lines or the electrolyte in the capacitor. The equivalent series resistance (ESR) is the amount of internal series resistance one would add to a perfect capacitor to model this. Some types of capacitors, primarily tantalum and aluminum electrolytic capacitors, as well as some film capacitors have a specified rating value for maximum ripple current.

- Tantalum electrolytic capacitors with solid manganese dioxide electrolyte are limited by ripple current and generally have the highest ESR ratings in the capacitor family. Exceeding their ripple limits can lead to shorts and burning parts.
- Aluminum electrolytic capacitors, the most common type of electrolytic, suffer a shortening of life expectancy at higher ripple currents. If ripple current exceeds the rated value of the capacitor, it tends to result in explosive failure.
- Ceramic capacitors generally have no ripple current limitation and have some of the lowest ESR ratings.
- Film capacitors have very low ESR ratings but exceeding rated ripple current may cause degradation failures.

Capacitance instability

The capacitance of certain capacitors decreases as the component ages. In ceramic capacitors, this is caused by degradation of the dielectric. The type of dielectric, ambient operating and storage temperatures are the most significant aging factors, while the operating voltage has a smaller effect. The aging process may be reversed by heating the component above the Curie point. Aging is fastest near the beginning of life of the component, and the device stabilizes over time.[26] Electrolytic capacitors age as the electrolyte evaporates. In contrast with ceramic capacitors, this occurs towards the end of life of the component.

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

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

Current and voltage reversal

Current reversal occurs when the current changes direction. Voltage reversal is the change of polarity in a circuit. Reversal is generally described as the percentage of the maximum rated voltage that reverses polarity. In DC circuits, this will usually be less than 100% (often in the range of 0 to 90%), whereas AC circuits experience 100% reversal.

In DC circuits and pulsed circuits, current and voltage reversal are affected by the damping of the system. Voltage reversal is encountered in RLC circuits that are underdamped. The current and voltage reverse direction, forming a harmonic oscillator between the inductance and capacitance. The current and voltage will tend to oscillate and may reverse direction several times, with each peak being lower than the previous, until the system reaches an equilibrium. This is often referred to as ringing. In comparison, critically damped or over-damped systems usually do not experience a voltage reversal. Reversal is also encountered in AC circuits, where the peak current will be equal in each direction.

For maximum life, capacitors usually need to be able to handle the maximum amount of reversal that a system will experience. An AC circuit will experience 100% voltage reversal, while under-damped DC circuits will experience less than 100%. Reversal creates excess electric fields in the dielectric, causes excess heating of both the dielectric and the conductors, and can dramatically shorten the life expectancy of the capacitor. Reversal ratings will often affect the design considerations for the capacitor, from the choice of dielectric materials and voltage ratings to the types of internal connections used.[27]

Dielectric absorption

Capacitors made with any type of dielectric material will show some level of "dielectric absorption" or “soakage”. On discharging a capacitor and disconnecting it, after a short time it may develop a voltage due to hysteresis in the dielectric. This effect can be objectionable in applications such as precision sample and hold circuits or timing circuits. The level of absorption depends on many factors, from design considerations to charging time, since the absorption is a time-dependent process. However, the primary factor is the type of dielectric material. Capacitors such as tantalum electrolytic or polysulfone film exhibit very high absorption, while polystyrene or Teflon allow very small levels of absorption.[28] In some capacitors where dangerous voltages and energies exist, such as in flashtubes, television sets, and defibrillators, the dielectric absorption can recharge the capacitor to hazardous voltages after it has been shorted or discharged. Any capacitor containing over 10 joules of energy is generally considered hazardous, while 50 joules or higher is potentially lethal. A capacitor may regain anywhere from 0.01 to 20% of its original charge over a period of several minutes, allowing a seemingly safe capacitor to become surprisingly dangerous.[29][30][31][32][33]

Leakage

Leakage is equivalent to a resistor in parallel with the capacitor. Constant exposure to heat can cause dielectric breakdown and excessive leakage, a problem often seen in older vacuum tube circuits, particularly where oiled paper and foil capacitors were used. In many vacuum tube circuits, interstage coupling capacitors are used to conduct a varying signal from the plate of one tube to the grid circuit of the next stage. A leaky capacitor can cause the grid circuit voltage to be raised from its normal bias setting, causing excessive current or signal distortion in the downstream tube. In power amplifiers this can cause the plates to glow red, or current limiting resistors to overheat, even fail. Similar considerations apply to component fabricated solid-state (transistor) amplifiers, but owing to lower heat production and the use of modern polyester dielectric barriers this once-common problem has become relatively rare.

Electrolytic failure from disuse

Aluminum electrolytic capacitors are *conditioned* when manufactured by applying a voltage sufficient to initiate the proper internal chemical state. This state is maintained by regular use of the equipment. If a system using electrolytic capacitors is unused for a long period of time it can lose its conditioning. Sometimes they fail with a short circuit when next operated.

2.3.4 Capacitor types

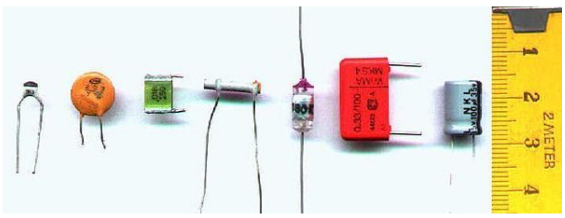
Main article: Types of capacitor

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

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

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

Dielectric materials



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

Most types of capacitor include a dielectric spacer, which increases their capacitance. These dielectrics are most often insulators. However, low capacitance devices are available with a vacuum between their plates, which allows extremely high voltage operation and low losses. Variable capacitors with their plates open to the atmosphere were commonly used in radio tuning circuits.

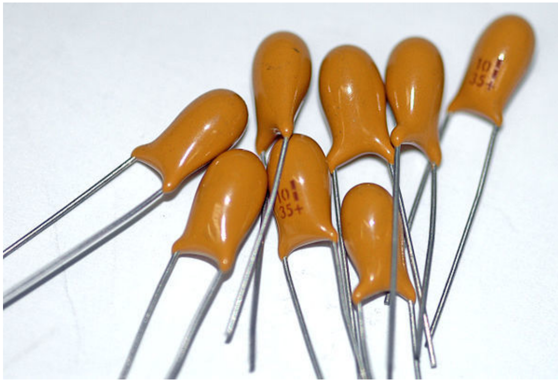
Later designs use polymer foil dielectric between the moving and stationary plates, with no significant air space between them.

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

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

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

Tantalum capacitors offer better frequency and temperature characteristics than aluminum, but higher dielectric absorption and leakage.[34]



Solid electrolyte, resin-dipped 10 μF 35 V tantalum capacitors. The **+** *sign indicates the positive lead.*

Polymer capacitors (OS-CON, OC-CON, KO, AO) use solid conductive polymer (or polymerized organic semiconductor) as electrolyte and offer longer life and lower ESR at higher cost than standard electrolytic capacitors.

A feedthrough capacitor is a component that, while not serving as its main use, has capacitance and is used to conduct signals through a conductive sheet.

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

Voltage-dependent capacitors

The dielectric constant for a number of very useful dielectrics changes as a function of the applied electrical field, for example ferroelectric materials, so the capacitance for these devices is more complex. For example, in charging such a capacitor the differential increase in voltage with charge is governed by:

$$dQ = C(V)\,dV$$

where the voltage dependence of capacitance, $C(V)$, suggests that the capacitance is a function of the electric field strength, which in a large area parallel plate device is given by $\varepsilon = V/d$. This field polarizes the dielectric, which polarization, in the case of a ferroelectric, is a nonlinear *S*-shaped function of the electric field, which, in the case of a large area parallel plate device, translates into a capacitance that is a nonlinear function of the voltage.[35][36]

Corresponding to the voltage-dependent capacitance, to charge the capacitor to voltage V an integral relation is found:

$$Q = \int_0^V C(V)\,dV$$

which agrees with $Q = CV$ only when C is not voltage independent.

By the same token, the energy stored in the capacitor now is given by

$$dW = Q\,dV = \left[\int_0^V dV'\,C(V')\right]\,dV\ .$$

Integrating:

$$W = \int_0^V dV \int_0^V dV'\,C(V') = \int_0^V dV' \int_{V'}^V dV\,C(V') = \int_0^V dV'\,(V - V')\,C(V')\ ,$$

where interchange of the order of integration is used.

The nonlinear capacitance of a microscope probe scanned along a ferroelectric surface is used to study the domain structure of ferroelectric materials.[37]

Another example of voltage dependent capacitance occurs in semiconductor devices such as semiconductor diodes, where the voltage dependence stems not from a change in dielectric constant but in a voltage dependence of the spacing between the charges on the two sides of the capacitor.[38] This effect is intentionally exploited in diode-like devices known as varicaps.

Frequency-dependent capacitors

If a capacitor is driven with a time-varying voltage that changes rapidly enough, at some frequency the polarization of the dielectric cannot follow the voltage. As an example of the origin of this mechanism, the internal microscopic dipoles contributing to the dielectric constant cannot move instantly, and so as frequency of an applied alternating voltage increases, the dipole response is limited and the dielectric constant diminishes. A changing dielectric constant with frequency is referred to as dielectric dispersion, and is governed by dielectric relaxation processes, such as Debye relaxation. Under transient conditions, the displacement field can be expressed as (see electric susceptibility):

$$\boldsymbol{D(t)} = \varepsilon_0 \int_{-\infty}^{t} \varepsilon_r(t - t')\boldsymbol{E}(t')\,dt',$$

indicating the lag in response by the time dependence of εr, calculated in principle from an underlying microscopic analysis, for example, of the dipole behavior in the dielectric. See, for example, linear response function.[39][40] The integral extends over the entire past history up to the present time. A Fourier transform in time then results in:

$$\boldsymbol{D}(\omega) = \varepsilon_0\varepsilon_r(\omega)\boldsymbol{E}(\omega)\ ,$$

where $\varepsilon_r(\omega)$ is now a complex function, with an imaginary part related to absorption of energy from the field by the medium. See permittivity. The capacitance, being proportional to the dielectric constant, also exhibits this frequency behavior. Fourier transforming Gauss's law with this form for displacement field:

$$I(\omega) = j\omega Q(\omega) = j\omega \oint_\Sigma \boldsymbol{D}(\boldsymbol{r},\ \omega)\cdot d\boldsymbol{\Sigma}$$

$$= [G(\omega) + j\omega C(\omega)]\,V(\omega) = \frac{V(\omega)}{Z(\omega)}\ ,$$

where j is the imaginary unit, $V(\omega)$ is the voltage component at angular frequency ω, $G(\omega)$ is the *real* part of the current, called the *conductance*, and $C(\omega)$ determines the *imaginary* part of the current and is the *capacitance*. $Z(\omega)$ is the complex impedance.

When a parallel-plate capacitor is filled with a dielectric, the measurement of dielectric properties of the medium is based upon the relation:

$$\varepsilon_r(\omega) = \varepsilon'_r(\omega) - j\varepsilon''_r(\omega) = \frac{1}{j\omega Z(\omega)C_0} = \frac{C_{\text{cmplx}}(\omega)}{C_0}\ ,$$

where a single *prime* denotes the real part and a double *prime* the imaginary part, $Z(\omega)$ is the complex impedance with the dielectric present, $C_{\text{cmplx}}(\omega)$ is the so-called *complex* capacitance with the dielectric present, and C_0 is the capacitance without the dielectric.[41][42] (Measurement "without the dielectric" in principle means measurement in free space, an unattainable goal inasmuch as even the quantum vacuum is predicted to exhibit nonideal behavior, such as dichroism. For practical purposes, when measurement errors are taken into account, often a measurement in terrestrial vacuum, or simply a calculation of C_0, is sufficiently accurate.[43])

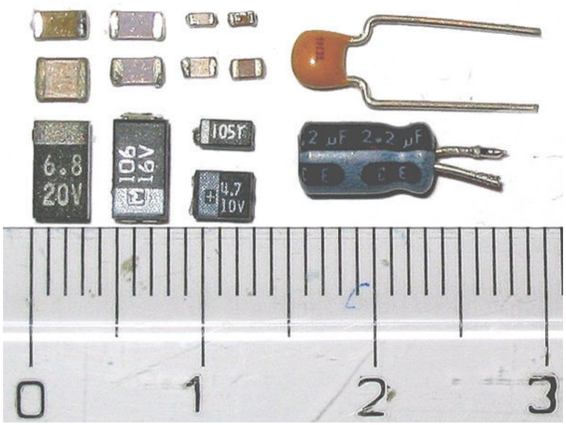
Using this measurement method, the dielectric constant may exhibit a resonance at certain frequencies corresponding to characteristic response frequencies (excitation energies) of contributors to the dielectric constant.

These resonances are the basis for a number of experimental techniques for detecting defects. The *conductance method* measures absorption as a function of frequency.[44] Alternatively, the time response of the capacitance can be used directly, as in *deep-level transient spectroscopy*.[45]

Another example of frequency dependent capacitance occurs with MOS capacitors, where the slow generation of minority carriers means that at high frequencies the capacitance measures only the majority carrier response, while at low frequencies both types of carrier respond.[46][47]

At optical frequencies, in semiconductors the dielectric constant exhibits structure related to the band structure of the solid. Sophisticated modulation spectroscopy measurement methods based upon modulating the crystal structure by pressure or by other stresses and observing the related changes in absorption or reflection of light have advanced our knowledge of these materials.[48]

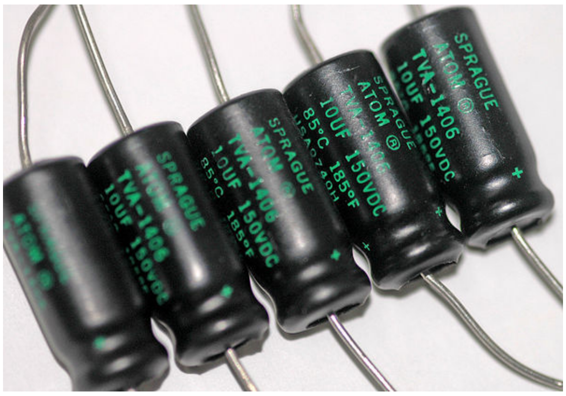
Structure



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

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

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



Several axial-lead electrolytic capacitors

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

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

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

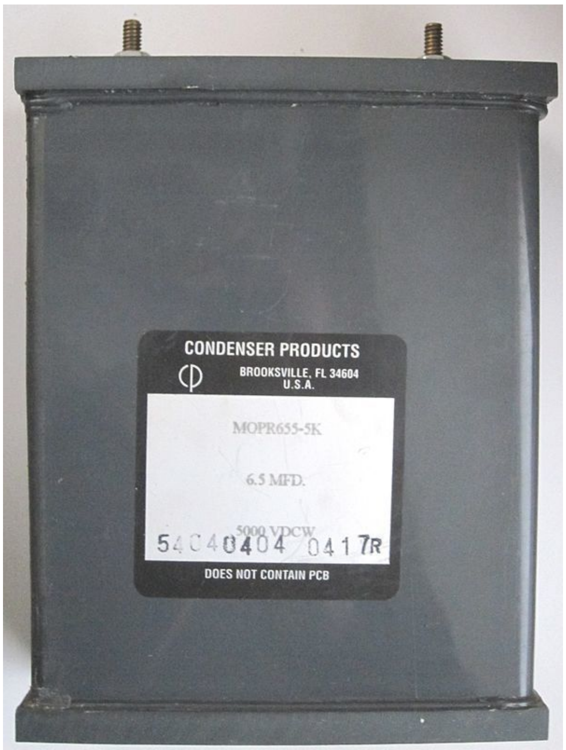
2.3.5 Capacitor markings

See also: Preferred number § E series

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

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

For typographical reasons, some manufacturers print "MF" on capacitors to indicate microfarads (μF).[49]



This mylar-film, oil-filled capacitor has very low inductance and low resistance, to provide the high-power (70 megawatt) and high speed (1.2 microsecond) discharge needed to operate a dye laser.

Example

A capacitor with the text **473K 330V** on its body has a capacitance of 47×10^3 pF = 47 nF (±10%) with a working voltage of 330 V. The working voltage of a capacitor is the highest voltage that can be applied across it without undue risk of breaking down the dielectric layer.

2.3.6 Applications

Main article: Applications of capacitors

Energy storage

A capacitor can store electric energy when disconnected from its charging circuit, so it can be used like a temporary battery, or like other types of rechargeable energy storage system.[50] Capacitors are commonly used in electronic devices to maintain power supply while batteries are being changed. (This prevents loss of information in volatile memory.)

Conventional capacitors provide less than 360 joules per kilogram of specific energy, whereas a conventional alkaline battery has a density of 590 kJ/kg.

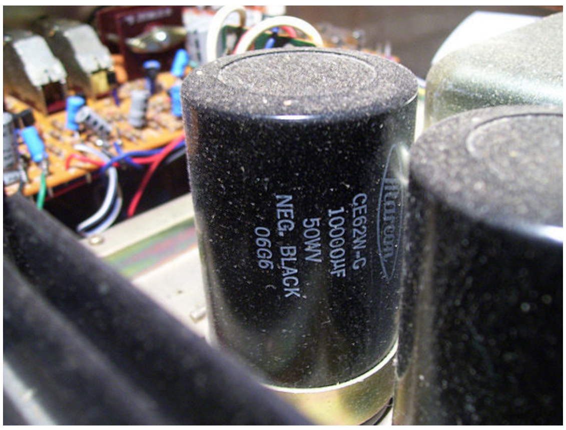
In car audio systems, large capacitors store energy for the amplifier to use on demand. Also for a flash tube a capacitor is used to hold the high voltage.

Pulsed power and weapons

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

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

Power conditioning



A 10,000 microfarad capacitor in an amplifier power supply

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

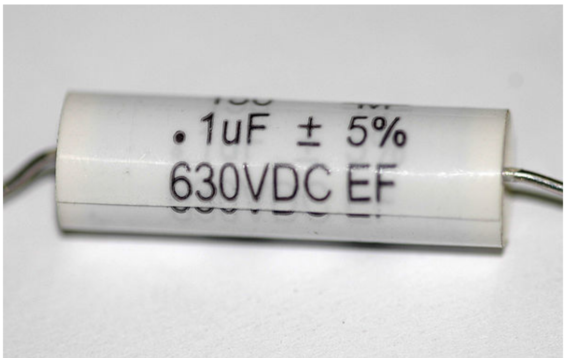
Capacitors are connected in parallel with the power circuits of most electronic devices and larger systems (such as factories) to shunt away and conceal current fluctuations from the primary power source to provide a "clean" power supply for signal or control circuits. Audio equipment, for example, uses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

A high-voltage capacitor bank used for power factor correction on a power transmission system

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

Suppression and coupling

Signal coupling Main article: capacitive coupling
Because capacitors pass AC but block DC signals (when



Polyester film capacitors are frequently used as coupling capacitors.

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

Decoupling Main article: decoupling capacitor

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

Decoupling capacitors need not always be discrete components. Capacitors used in these applications may be built into a printed circuit board, between the various layers. These are often referred to as embedded capacitors.[51] The layers in the board contributing to the capacitive properties also function as power and ground planes, and have a dielectric in between them, enabling them to operate as a parallel plate capacitor.

High-pass and low-pass filters Further information: High-pass filter and Low-pass filter

Noise suppression, spikes, and snubbers Further information: High-pass filter and Low-pass filter

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

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

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

Motor starters

Main article: motor capacitor

In single phase squirrel cage motors, the primary winding within the motor housing is not capable of starting a rotational motion on the rotor, but is capable of sustaining one. To start the motor, a secondary "start" winding has a series non-polarized *starting capacitor* to introduce a lead in the sinusoidal current. When the secondary (start) winding is placed at an angle with respect to the primary (run) winding, a rotating electric field is created. The force of the rotational field is not constant, but is sufficient to start the rotor spinning. When the rotor comes close to operating speed, a centrifugal switch (or current-sensitive relay in series with the main winding) disconnects the capacitor. The start capacitor is typically mounted to the side of the motor housing. These are called capacitor-start motors, that have relatively high starting torque. Typically they can have up-to four times as much starting torque than a split-phase motor and are used on applications such as compressors, pressure washers and any small device requiring high starting torques.

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

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

Signal processing

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

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

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

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

where L is in henries and C is in farads.

Sensing

Main article: capacitive sensing

Main article: Capacitive displacement sensor

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

Changing the dielectric:

> The effects of varying the characteristics of the **dielectric** can be used for sensing purposes. Capacitors with an exposed and porous dielectric can be used to measure humidity in air. Capacitors are used to accurately measure the fuel level in airplanes; as the fuel covers more of a pair of plates, the circuit capacitance increases. Squeezing the dielectric can change a capacitor at a few tens of bar pressure sufficiently that it

can be used as a pressure sensor.[52] A selected, but otherwise standard, polymer dielectric capacitor, when immersed in a compatible gas or liquid, can work usefully as a very low cost pressure sensor up to many hundreds of bar.

Changing the distance between the plates:

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

Changing the effective area of the plates:

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

Oscillators

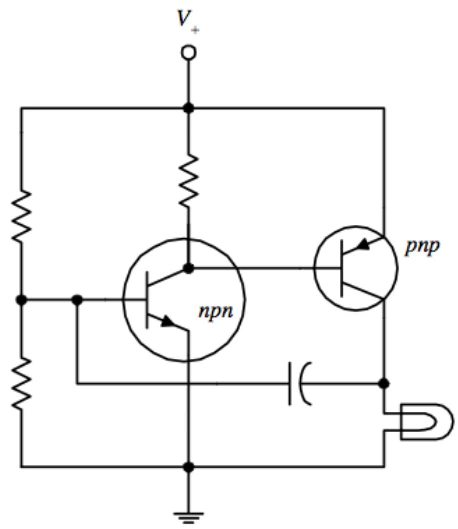
Further information: Hartley oscillator

A capacitor can possess spring-like qualities in an oscillator circuit. In the image example, a capacitor acts to influence the biasing voltage at the npn transistor's base. The resistance values of the voltage-divider resistors and the capacitance value of the capacitor together control the oscillatory frequency.

Producing light

Main article: light emitting capacitor

A light-emitting capacitor is made from a dielectric that uses phosphorescence to produce light. If one of the conductive plates is made with a transparent material, the light will be visible. Light-emitting capacitors are used in the construction of electroluminescent panels, for applications such as backlighting for laptop computers. In this case, the entire panel is a capacitor used for the purpose of generating light.



Example of a simple oscillator that requires a capacitor to function

2.3.7 Hazards and safety

The hazards posed by a capacitor are usually determined, foremost, by the amount of energy stored, which is the cause of things like electrical burns or heart fibrillation. Factors such as voltage and chassis material are of secondary consideration, which are more related to how easily a shock can be initiated rather than how much damage can occur.[33]

Capacitors may retain a charge long after power is removed from a circuit; this charge can cause dangerous or even potentially fatal shocks or damage connected equipment. For example, even a seemingly innocuous device such as a disposable-camera flash unit, powered by a 1.5 volt AA battery, has a capacitor which may contain over 15 joules of energy and be charged to over 300 volts. This is easily capable of delivering a shock. Service procedures for electronic devices usually include instructions to discharge large or high-voltage capacitors, for instance using a Brinkley stick. Capacitors may also have built-in discharge resistors to dissipate stored energy to a safe level within a few seconds after power is removed. High-voltage capacitors are stored with the terminals shorted, as protection from potentially dangerous voltages due to dielectric absorption or from transient voltages the capacitor may pick up from static charges or passing weather events.[33]

Some old, large oil-filled paper or plastic film capacitors contain polychlorinated biphenyls (PCBs). It is known that waste PCBs can leak into groundwater under landfills. Capacitors containing PCB were labelled as containing "Askarel" and several other trade names.

PCB-filled paper capacitors are found in very old (pre-1975) fluorescent lamp ballasts, and other applications.

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

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

- Swollen caps of electrolytic capacitors – special design of semi-cut caps prevents capacitors from bursting
- This high-energy capacitor from a defibrillator can deliver over 500 joules of energy. A resistor is connected between the terminals for safety, to allow the stored energy to be released.
- Catastrophic failure

2.3.8 See also

- Capacitance meter
- Capacitor types
- Capacitor plague
- Circuit design
- Electric displacement field
- Electroluminescence
- Electronic oscillator
- Gimmick capacitor
- Vacuum variable capacitor

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- Introduction to Capacitor and Capacitor codes
- Low ESR Capacitor Manufacturers
- How Capacitor Works – Capacitor Markings and Color Codes

2.4 Inductor

Axial lead inductors (100 µH)

An **inductor**, also called a **coil** or **reactor**, is a passive two-terminal electrical component which resists changes in electric current passing through it. It consists of a conductor such as a wire, usually wound into a coil. Energy is stored in a magnetic field in the coil as long as current flows. When the current flowing through an inductor changes, the time-varying magnetic field induces a voltage in the conductor, according to Faraday's law of electromagnetic induction. According to Lenz's law the direction of induced electromotive force (or "e.m.f.") is always such that it opposes the change in current that created it. As a result, inductors always oppose a change in current, in the same way that a flywheel opposes a change in rotational velocity. Care should be taken not to confuse this with the resistance provided by a resistor.

An inductor is characterized by its *inductance*, the ratio of the voltage to the rate of change of current, which has units of henries (H). Inductors have values that typically range from 1 µH (10^{-6}H) to 1 H. Many inductors have a magnetic core made of iron or ferrite inside the coil, which serves to increase the magnetic field and thus the inductance. Along with capacitors and resistors, inductors are one of the three passive linear circuit elements that make up electric circuits. Inductors are widely used in alternating current (AC) electronic equipment, particularly in radio equipment. They are used to block AC while allowing DC to pass; inductors designed for this purpose are called chokes. They are also used in electronic filters to separate signals of different frequencies, and in combination with capacitors to make tuned circuits, used to tune radio and TV receivers.

2.4.1 Overview

Inductance (L) results from the magnetic field around a current-carrying conductor; the electric current through the conductor creates a magnetic flux. Mathematically speaking, inductance is determined by how much magnetic flux φ through the circuit is created by a given current i[1][2][3][4]

$$L = \frac{\phi}{i} \quad (1)$$

Inductors that have ferromagnetic cores are nonlinear; the inductance changes with the current, in this more general case inductance is defined as

$$L = \frac{d\phi}{di}$$

Any wire or other conductor will generate a magnetic field when current flows through it, so every conductor has some inductance. The inductance of a circuit depends on the geometry of the current path as well as the magnetic permeability of nearby materials. An inductor is a component consisting of a wire or other conductor shaped to increase the magnetic flux through the circuit, usually in the shape of a coil or helix. Winding the wire into a coil increases the number of times the magnetic flux lines link the circuit, increasing the field and thus the inductance. The more turns, the higher the inductance. The inductance also depends on the shape of the coil, separation of the turns, and many other factors. By adding a "magnetic core" made of a ferromagnetic material like iron inside the coil, the magnetizing field from the coil will induce magnetization in the material, increasing the magnetic flux. The high permeability of a ferromagnetic core can increase the inductance of a coil by a factor of several thousand over what it would be without it.

Constitutive equation

Any change in the current through an inductor creates a changing flux, inducing a voltage across the inductor. By Faraday's law of induction, the voltage induced by any change in magnetic flux through the circuit is[4]

$$v = \frac{d\phi}{dt}$$

From (1) above[4]

$$v = \frac{d}{dt}(Li) = L\frac{di}{dt} \quad (2)$$

So inductance is also a measure of the amount of electromotive force (voltage) generated for a given rate of change of current. For example, an inductor with an inductance of 1 henry produces an EMF of 1 volt when the current through the inductor changes at the rate of 1 ampere per second. This is usually taken to be the constitutive relation (defining equation) of the inductor.

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

Lenz's law

The polarity (direction) of the induced voltage is given by Lenz's law, which states that it will be such as to oppose the change in current. For example, if the current through an inductor is increasing, the induced voltage will be positive at the terminal through which the current enters and negative at the terminal through which it leaves, tending to oppose the additional current. The energy from the external circuit necessary to overcome this potential "hill" is being stored in the magnetic field of the inductor; the inductor is said to be "charging" or "energizing". If the current is decreasing, the induced voltage will be negative at the terminal through which the current enters and positive at the terminal through which it leaves, tending to maintain the current. Energy from the magnetic field is being returned to the circuit; the inductor is said to be "discharging".

Ideal and real inductors

In circuit theory, inductors are idealized as obeying the mathematical relation (2) above precisely. An "ideal inductor" has inductance, but no resistance or capacitance, and does not dissipate or radiate energy. However real inductors have side effects which cause their behavior to depart from this simple model. They have resistance (due to the resistance of the wire and energy losses in core material), and parasitic capacitance (due to the electric field between the turns of wire which are at slightly different potentials). At high frequencies the capacitance begins to affect the inductor's behavior; at some frequency, real inductors behave as resonant circuits, becoming self-resonant. Above the resonant frequency the capacitive reactance becomes the dominant part of the impedance. At higher frequencies, resistive losses in the windings increase due to skin effect and proximity effect.

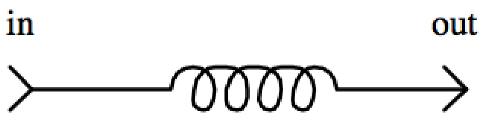
Inductors with ferromagnetic cores have additional energy losses due to hysteresis and eddy currents in the core, which increase with frequency. At high currents, iron core inductors also show gradual departure from ideal behavior due to nonlinearity caused by magnetic saturation of the core. An inductor may radiate electromagnetic energy into surrounding space and circuits, and may absorb electromagnetic emissions from other circuits, causing electromagnetic interference (EMI). Real-world inductor applications may consider these parasitic parameters as important as the inductance.

2.4.2 Applications

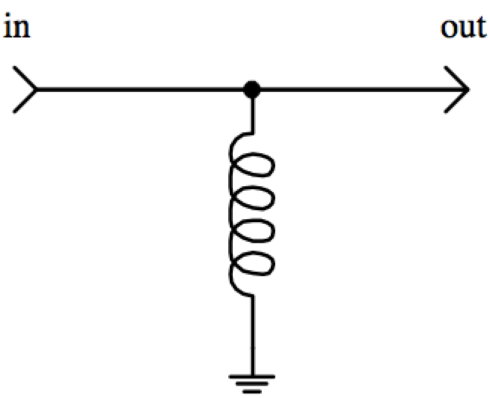
Large 50 MVAR three-phase iron-core loading inductor at an Austrian utility substation

Inductors are used extensively in analog circuits and signal processing. Applications range from the use of large inductors in power supplies, which in conjunction with filter capacitors remove residual hums known as the mains hum or other fluctuations from the direct current output, to the small inductance of the ferrite bead or torus installed around a cable to prevent radio frequency interference from being transmitted down the wire. Inductors are used as the energy storage device in many switched-mode power supplies to produce DC current. The inductor supplies energy to the circuit to keep current flowing during the "off" switching periods.

A ferrite "bead" choke, consisting of an encircling ferrite cylinder, removes electronic noise from a computer power cord.



Example of signal filtering. In this configuration, the inductor blocks AC current, while allowing DC current to pass.



Example of signal filtering. In this configuration, the inductor decouples DC current, while allowing AC current to pass.

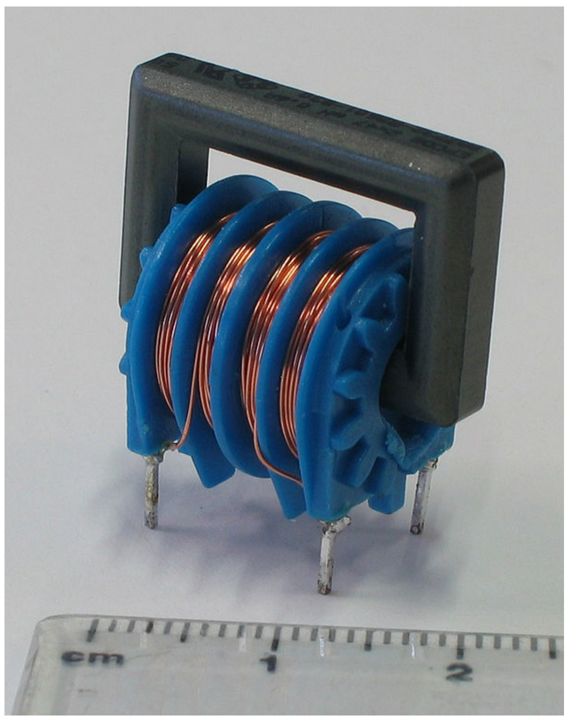
An inductor connected to a capacitor forms a tuned circuit, which acts as a resonator for oscillating current. Tuned circuits are widely used in radio frequency equipment such as radio transmitters and receivers, as narrow bandpass filters to select a single frequency from a composite signal, and in electronic oscillators to generate sinusoidal signals.

Two (or more) inductors in proximity that have coupled magnetic flux (mutual inductance) form a transformer, which is a fundamental component of every electric utility power grid. The efficiency of a transformer may decrease as the frequency increases due to eddy currents in the core material and skin effect on the windings. The size of the core can be decreased at higher frequencies. For this reason, aircraft use 400 hertz alternating current rather than the usual 50 or 60 hertz, allowing a great saving in weight from the use of smaller transformers.[5]

Inductors are also employed in electrical transmission systems, where they are used to limit switching currents and fault currents. In this field, they are more commonly referred to as reactors.

Because inductors have complicated side effects (detailed below) which cause them to depart from ideal behavior, because they can radiate electromagnetic interference (EMI), and most of all because of their bulk which prevents them from being integrated on semiconductor chips, the use of inductors is declining in modern electronic devices, particularly compact portable devices. Real inductors are increasingly being replaced by active circuits such as the gyrator which can synthesize inductance using capacitors.

2.4.3 Inductor construction



A ferrite core inductor with two 47 mH windings.

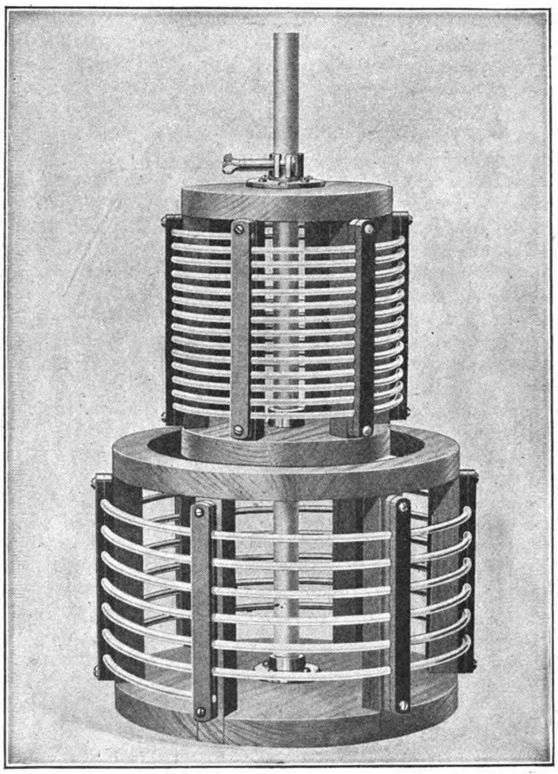
An inductor usually consists of a coil of conducting material, typically insulated copper wire, wrapped around a core either of plastic or of a ferromagnetic (or ferrimagnetic) material; the latter is called an "iron core" inductor. The high permeability of the ferromagnetic core increases the magnetic field and confines it closely to the inductor, thereby increasing the inductance. Low frequency inductors are constructed like transformers, with cores of electrical steel laminated to prevent eddy currents. 'Soft' ferrites are widely used for cores above audio frequencies, since they do not cause the large energy losses at high frequencies that ordinary iron alloys do. Inductors come in many shapes. Most are constructed as enamel coated wire (magnet wire) wrapped around a ferrite bobbin with wire exposed on the outside, while some enclose the wire completely in ferrite and are referred to as “shielded”. Some inductors have an adjustable core, which enables changing of the inductance. Inductors used to block very high frequencies are sometimes made by stringing a ferrite bead on a wire.

Small inductors can be etched directly onto a printed circuit board by laying out the trace in a spiral pattern. Some such planar inductors use a planar core.

Small value inductors can also be built on integrated circuits using the same processes that are used to make transistors. Aluminium interconnect is typically used, laid out in a spiral coil pattern. However, the small dimensions limit the inductance, and it is far more common to use a circuit called a "gyrator" that uses a capacitor and active components to behave similarly to an inductor.

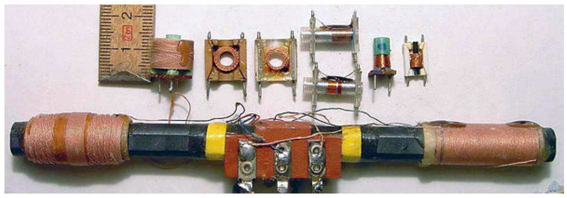
2.4.4 Types of inductor

Air core inductor



Resonant oscillation transformer from a spark gap transmitter. Coupling can be adjusted by moving the top coil on the support rod. Shows high Q construction with spaced turns of large diameter tubing.

The term *air core coil* describes an inductor that does not use a magnetic core made of a ferromagnetic material. The term refers to coils wound on plastic, ceramic, or other nonmagnetic forms, as well as those that have only air inside the windings. Air core coils have lower inductance than ferromagnetic core coils, but are often used at high frequencies because they are free from energy losses called core losses that occur in ferromagnetic cores, which increase with frequency. A side effect that can occur in air core coils in which the winding is not rigidly supported on a form is 'microphony': mechanical vibration of the windings can cause variations in the inductance.

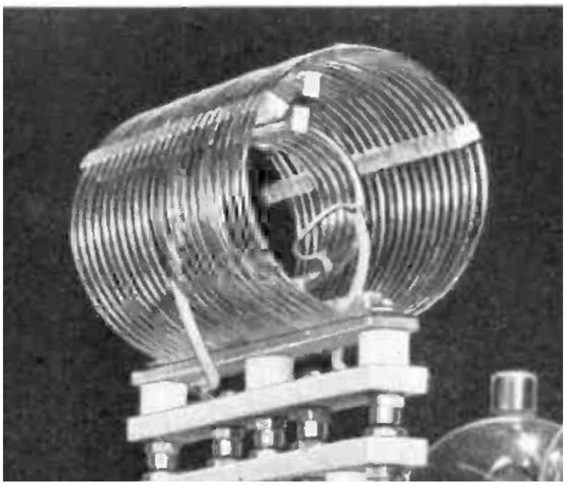


Collection of RF inductors, showing techniques to reduce losses. The three top left and the ferrite loopstick or rod antenna,[6][7][8][9] bottom, have basket windings.

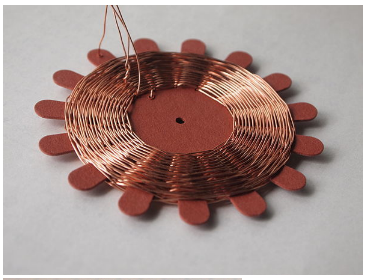
Radio frequency inductor At high frequencies, particularly radio frequencies (RF), inductors have higher resistance and other losses. In addition to causing power loss, in resonant circuits this can reduce the Q factor of the circuit, broadening the bandwidth. In RF inductors, which are mostly air core types, specialized construction techniques are used to minimize these losses. The losses are due to these effects:

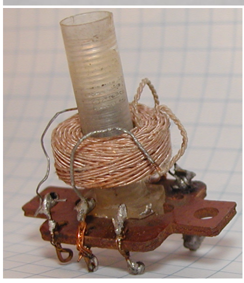
- **Skin effect**: The resistance of a wire to high frequency current is higher than its resistance to direct current because of skin effect. Radio frequency alternating current does not penetrate far into the body of a conductor but travels along its surface. Therefore, in a solid wire, most of the cross sectional area of the wire is not used to conduct the current, which is in a narrow annulus on the surface. This effect increases the resistance of the wire in the coil, which may already have a relatively high resistance due to its length and small diameter.

- **Proximity effect**: Another similar effect that also increases the resistance of the wire at high frequencies is proximity effect, which occurs in parallel wires that lie close to each other. The individual magnetic field of adjacent turns induces eddy currents in the wire of the coil, which causes the current in the conductor to be concentrated in a thin strip on the side near the adjacent wire. Like skin effect, this reduces the effective cross-sectional area of the wire conducting current, increasing its resistance.



High Q tank coil in a shortwave transmitter





(left) Spiderweb coil *(right)* Adjustable ferrite slug-tuned RF coil with basketweave winding and litz wire

- **Dielectric losses**: The high frequency electric field near the conductors in a tank coil can cause the motion of polar molecules in nearby insulating materials, dissipating energy as heat. So coils used for tuned circuits are often not wound on coil forms but are suspended in air, supported by narrow plastic or ceramic strips.

- **Parasitic capacitance**: The capacitance between individual wire turns of the coil, called parasitic capacitance, does not cause energy losses but can change the behavior of the coil. Each turn of the coil is at a slightly different potential, so the electric field between neighboring turns stores charge on the wire, so the coil acts as if it has a capacitor in parallel with it. At a high enough frequency this capacitance can resonate with the inductance of the coil forming a tuned circuit, causing the coil to become self-resonant.

To reduce parasitic capacitance and proximity effect, high Q RF coils are constructed to avoid having many turns lying close together, parallel to one another. The windings of RF coils are often limited to a single layer, and the turns are spaced apart. To reduce resistance due to skin effect, in high-power inductors such as those used in transmitters the windings are sometimes made of a metal strip or tubing which has a larger surface area, and the surface is silver-plated.

- **Basket-weave coils**: To reduce proximity effect and parasitic capacitance, multilayer RF coils are wound in patterns in which successive turns are not parallel but crisscrossed at an angle; these are often called *honeycomb* or *basket-weave* coils. These are occasionally wound on a vertical insulating supports with dowels or slots, with the wire weaving in and out through the slots.

- **Spiderweb coils**: Another construction technique with similar advantages is flat spiral coils.These are often wound on a flat insulating support with radial spokes or slots, with the wire weaving in and out through the slots; these are called *spiderweb* coils. The form has an odd number of slots, so successive turns of the spiral lie on opposite sides of the form, increasing separation.

- **Litz wire**: To reduce skin effect losses, some coils are wound with a special type of radio frequency wire called litz wire. Instead of a single solid conductor, litz wire consists of a number of smaller wire strands that carry the current. Unlike ordinary stranded wire, the strands are insulated from each other, to prevent skin effect from forcing the current to the surface, and are twisted or braided together. The twist pattern ensures that each wire strand spends the same amount of its length on the outside of the wire bundle, so skin effect distributes the current equally between the strands, resulting in a larger cross-sectional conduction area than an equivalent single wire.

Ferromagnetic core inductor

Ferromagnetic-core or iron-core inductors use a magnetic core made of a ferromagnetic or ferrimagnetic material such as iron or ferrite to increase the inductance. A magnetic core can increase the inductance of a coil by a factor of several thousand, by increasing the magnetic field due to its higher magnetic permeability. However the magnetic properties of the core material cause several side effects which alter the behavior of the inductor and require special construction:

- Core losses: A time-varying current in a ferromagnetic inductor, which causes a time-varying magnetic field in its core, causes energy losses in the core

A variety of types of ferrite core inductors and transformers

material that are dissipated as heat, due to two processes:

- Eddy currents: From Faraday's law of induction, the changing magnetic field can induce circulating loops of electric current in the conductive metal core. The energy in these currents is dissipated as heat in the resistance of the core material. The amount of energy lost increases with the area inside the loop of current.
- Hysteresis: Changing or reversing the magnetic field in the core also causes losses due to the motion of the tiny magnetic domains it is composed of. The energy loss is proportional to the area of the hysteresis loop in the BH graph of the core material. Materials with low coercivity have narrow hysteresis loops and so low hysteresis losses.

For both of these processes, the energy loss per cycle of alternating current is constant, so core losses increase linearly with frequency. Online core loss calculators[10] are available to calculate the energy loss. Using inputs such as input voltage, output voltage, output current, frequency, ambient temperature, and inductance these calculators can predict the losses of the inductors core and AC/DC based on the operating condition of the circuit being used.[11]

- Nonlinearity: If the current through a ferromagnetic core coil is high enough that the magnetic core saturates, the inductance will not remain constant but will change with the current through the device. This is called nonlinearity and results in distortion of the signal. For example, audio signals can suffer intermodulation distortion in saturated inductors. To prevent this, in linear circuits the current through iron core inductors must be limited below the saturation level. Some laminated cores have a narrow air gap in them for this purpose, and powdered iron cores have a distributed air gap. This allows higher levels of magnetic flux and thus higher currents through the inductor before it saturates.[12]

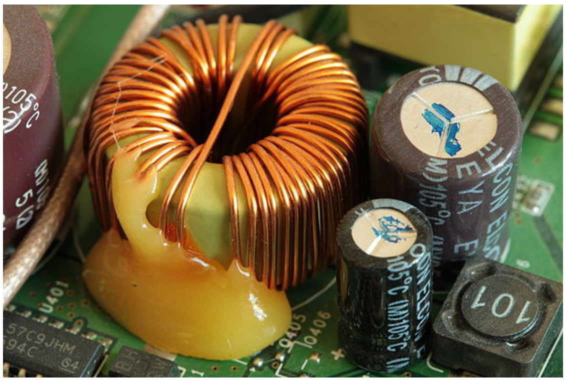
Laminated iron core ballast inductor for a metal halide lamp

Laminated core inductor Low-frequency inductors are often made with laminated cores to prevent eddy currents, using construction similar to transformers. The core is made of stacks of thin steel sheets or laminations oriented parallel to the field, with an insulating coating on the surface. The insulation prevents eddy currents between the sheets, so any remaining currents must be within the cross sectional area of the individual laminations, reducing the area of the loop and thus reducing the energy losses greatly. The laminations are made of low-coercivity silicon steel, to reduce hysteresis losses.

Ferrite-core inductor For higher frequencies, inductors are made with cores of ferrite. Ferrite is a ceramic ferrimagnetic material that is nonconductive, so eddy currents cannot flow within it. The formulation of ferrite is $xxFe_2O_4$ where xx represents various metals. For inductor cores soft ferrites are used, which have low coercivity and thus low hysteresis losses. Another similar material is powdered iron cemented with a binder.

Toroidal core inductor Main article: Toroidal inductors and transformers

In an inductor wound on a straight rod-shaped core, the

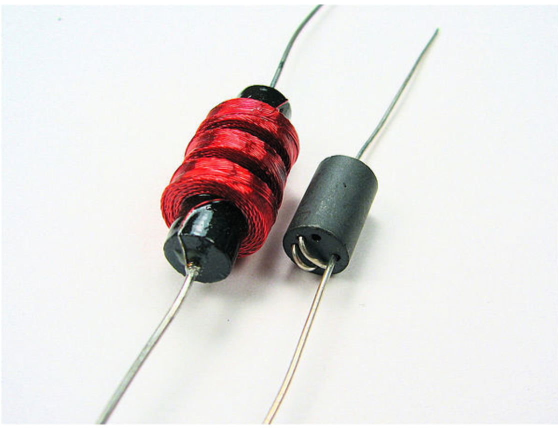


Toroidal inductor in the power supply of a wireless router

magnetic field lines emerging from one end of the core must pass through the air to re-enter the core at the other end. This reduces the field, because much of the magnetic field path is in air rather than the higher permeability core material. A higher magnetic field and inductance can be achieved by forming the core in a closed magnetic circuit. The magnetic field lines form closed loops within the core without leaving the core material. The shape often used is a toroidal or doughnut-shaped ferrite core. Because of their symmetry, toroidal cores allow a minimum of the magnetic flux to escape outside the core (called *leakage flux*), so they radiate less electromagnetic interference than other shapes. Toroidal core coils are manufactured of various materials, primarily ferrite, powdered iron and laminated cores.[13]

Choke Main article: Choke (electronics)

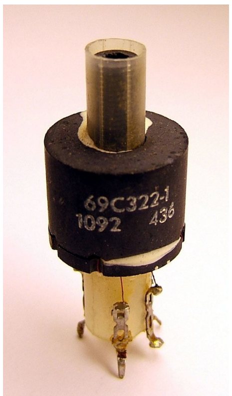
A choke is designed specifically for blocking higher-

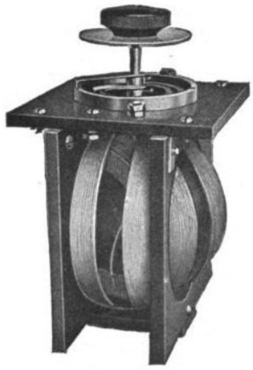


An MF or HF radio choke for tenths of an ampere, and a ferrite bead VHF choke for several amperes.

frequency alternating current (AC) in an electrical circuit, while allowing lower frequency or DC current to pass. It usually consists of a coil of insulated wire often wound on a magnetic core, although some consist of a donut-shaped "bead" of ferrite material strung on a wire. Like other inductors, chokes resist changes to the current passing through them, and so alternating currents of higher frequency, which reverse direction rapidly, are resisted more than currents of lower frequency; the choke's impedance increases with frequency. Its low electrical resistance allows both AC and DC to pass with little power loss, but it can limit the amount of AC passing through it due to its reactance.

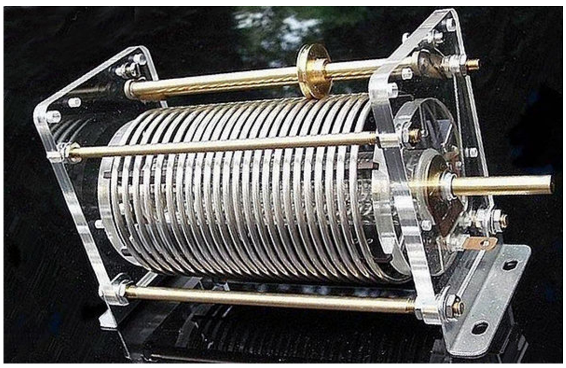
Variable inductor





(left) Inductor with a threaded ferrite slug *(visible at top)* that can be turned to move it into or out of the coil. 4.2 cm high. *(right)* A variometer used in radio receivers in the 1920s

Probably the most common type of variable inductor to-



A "roller coil", an adjustable air-core RF inductor used in the tuned circuits of radio transmitters. One of the contacts to the coil is made by the small grooved wheel, which rides on the wire. Turning the shaft rotates the coil, moving the contact wheel up or down the coil, allowing more or fewer turns of the coil into the circuit, to change the inductance.

day is one with a moveable ferrite magnetic core, which can be slid or screwed in or out of the coil. Moving the core farther into the coil increases the permeability, increasing the magnetic field and the inductance. Many inductors used in radio applications (usually less than 100 MHz) use adjustable cores in order to tune such inductors to their desired value, since manufacturing processes have certain tolerances (inaccuracy). Sometimes such cores for frequencies above 100 MHz are made from highly conductive non-magnetic material such as aluminum.[14] They decrease the inductance because the magnetic field must bypass them.

Air core inductors can use sliding contacts or multiple taps to increase or decrease the number of turns included in the circuit, to change the inductance. A type much used in the past but mostly obsolete today has a spring contact that can slide along the bare surface of the windings. The disadvantage of this type is that the contact usually short-circuits one or more turns. These turns act like a single-turn short-circuited transformer secondary winding; the large currents induced in them cause power losses.

A type of continuously variable air core inductor is the *variometer*. This consists of two coils with the same number of turns connected in series, one inside the other. The inner coil is mounted on a shaft so its axis can be turned with respect to the outer coil. When the two coils' axes are collinear, with the magnetic fields pointing in the same direction, the fields add and the inductance is maximum. When the inner coil is turned so its axis is at an angle with the outer, the mutual inductance between them is smaller so the total inductance is less. When the inner coil is turned 180° so the coils are collinear with their magnetic fields opposing, the two fields cancel each other and the inductance is very small. This type has the advantage that it is continuously variable over a wide range. It is used in antenna tuners and matching circuits to match low frequency transmitters to their antennas.

Another method to control the inductance without any moving parts requires an additional DC current bias winding which controls the permeability of an easily saturable core material. See Magnetic amplifier.

2.4.5 Circuit theory

The effect of an inductor in a circuit is to oppose changes in current through it by developing a voltage across it proportional to the rate of change of the current. An ideal inductor would offer no resistance to a constant direct current; however, only superconducting inductors have truly zero electrical resistance.

The relationship between the time-varying voltage $v(t)$ across an inductor with inductance L and the time-varying current $i(t)$ passing through it is described by the differential equation:

$$v(t) = L\frac{di(t)}{dt}$$

When there is a sinusoidal alternating current (AC) through an inductor, a sinusoidal voltage is induced. The amplitude of the voltage is proportional to the product of the amplitude (IP) of the current and the frequency (f) of the current.

$$\begin{aligned} i(t) &= I_\mathrm{P}\sin(2\pi ft) \\ \frac{di(t)}{dt} &= 2\pi fI_\mathrm{P}\cos(2\pi ft) \\ v(t) &= 2\pi fLI_\mathrm{P}\cos(2\pi ft) \end{aligned}$$

In this situation, the phase of the current lags that of the voltage by π/2 (90°). For sinusoids, as the voltage across the inductor goes to its maximum value, the current goes to zero, and as the voltage across the inductor goes to zero, the current through it goes to its maximum value.

If an inductor is connected to a direct current source with value I via a resistance R, and then the current source is short-circuited, the differential relationship above shows that the current through the inductor will discharge with an exponential decay:

$$i(t) = Ie^{-\frac{R}{L}t}$$

Reactance

The ratio of the peak voltage to the peak current in an inductor energised from a sinusoidal source is called the reactance and is denoted XL. The suffix is to distinguish inductive reactance from capacitive reactance due to capacitance.

$$X_\mathrm{L} = \frac{V_\mathrm{P}}{I_\mathrm{P}} = \frac{2\pi fLI_\mathrm{P}}{I_\mathrm{P}}$$

Thus,

$$X_\mathrm{L} = 2\pi fL$$

Reactance is measured in the same units as resistance (ohms) but is not actually a resistance. A resistor will dissipate energy as heat when a current passes. This does not happen with an inductor; rather, energy is stored in the magnetic field as the current builds and later returned to the circuit as the current falls. Inductive reactance is strongly frequency dependent. At low frequency the reactance falls, and for a steady current (zero frequency) the inductor behaves as a short-circuit. At increasing frequency, on the other hand, the reactance increases and at a sufficiently high frequency the inductor approaches an open circuit.

Laplace circuit analysis (s-domain)

When using the Laplace transform in circuit analysis, the impedance of an ideal inductor with no initial current is represented in the *s* domain by:

$$Z(s) = Ls$$

where

L is the inductance, and

s is the complex frequency.

If the inductor does have initial current, it can be represented by:

- adding a voltage source in series with the inductor, having the value:

$$LI_0$$

where

L is the inductance, and

I_0 is the initial current in the inductor.

(*Note that the source should have a polarity that is aligned with the initial current*)

- or by adding a current source in parallel with the inductor, having the value:

$$\frac{I_0}{s}$$

where

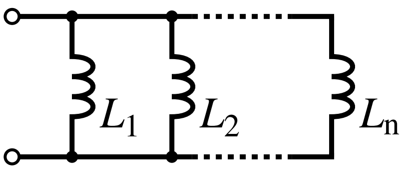
I_0 is the initial current in the inductor.

s is the complex frequency.

Inductor networks

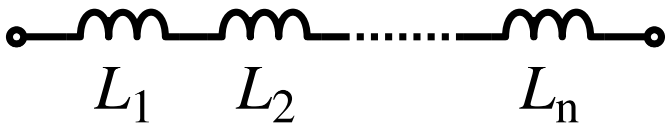
Main article: Series and parallel circuits

Inductors in a parallel configuration each have the same potential difference (voltage). To find their total equivalent inductance (L_{eq}):



$$\frac{1}{L_{\text{eq}}} = \frac{1}{L_1} + \frac{1}{L_2} + \cdots + \frac{1}{L_n}$$

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



$$L_{\text{eq}} = L_1 + L_2 + \cdots + L_n$$

These simple relationships hold true only when there is no mutual coupling of magnetic fields between individual inductors.

Stored energy

Neglecting losses, the energy (measured in joules, in SI) stored by an inductor is equal to the amount of work required to establish the current through the inductor, and therefore the magnetic field. This is given by:

$$E_{\text{stored}} = \frac{1}{2}LI^2$$

where L is inductance and I is the current through the inductor.

This relationship is only valid for linear (non-saturated) regions of the magnetic flux linkage and current relationship. In general if one decides to find the energy stored in a LTI inductor that has initial current in a specific time between t_0 and t_1 can use this:

$$E = \int_{t_0}^{t_1} P(t)\,dt = \frac{1}{2}LI(t_1)^2 - \frac{1}{2}LI(t_0)^2$$

2.4.6 *Q* factor

An ideal inductor would have no resistance or energy losses. However, real inductors have winding resistance from the metal wire forming the coils. Since the winding resistance appears as a resistance in series with the inductor, it is often called the *series resistance*. The inductor's series resistance converts electric current through the coils into heat, thus causing a loss of inductive quality. The quality factor (or *Q*) of an inductor is the ratio of its inductive reactance to its resistance at a given frequency, and is a measure of its efficiency. The higher the Q factor of the inductor, the closer it approaches the behavior of an ideal, lossless, inductor. High Q inductors are used with capacitors to make resonant circuits in radio transmitters and receivers. The higher the Q is, the narrower the bandwidth of the resonant circuit.

The Q factor of an inductor can be found through the following formula, where L is the inductance, R is the inductor's effective series resistance, ω is the radian operating frequency, and the product ωL is the inductive reactance:

$$Q = \frac{\omega L}{R}$$

Notice that Q increases linearly with frequency if L and R are constant. Although they are constant at low frequencies, the parameters vary with frequency. For example, skin effect, proximity effect, and core losses increase R with frequency; winding capacitance and variations in permeability with frequency affect L.

Qualitatively, at low frequencies and within limits, increasing the number of turns N improves Q because L varies as N^2 while R varies linearly with N. Similarly, increasing the radius r of an inductor improves Q because L varies as r^2 while R varies linearly with r. So high Q air core inductors often have large diameters and many turns. Both of those examples assume the diameter of the wire stays the same, so both examples use proportionally more wire (copper). If the total mass of wire is held constant, then there would be no advantage to increasing the number of turns or the radius of the turns because the wire would have to be proportionally thinner.

Using a high permeability ferromagnetic core can greatly increase the inductance for the same amount of copper, so the core can also increase the Q. Cores however also introduce losses that increase with frequency. The core material is chosen for best results for the frequency band. At VHF or higher frequencies an air core is likely to be used.

Inductors wound around a ferromagnetic core may saturate at high currents, causing a dramatic decrease in inductance (and Q). This phenomenon can be avoided by using a (physically larger) air core inductor. A well designed air core inductor may have a Q of several hundred.

2.4.7 Inductance formulas

See also: Inductance § Self-inductance of simple electrical circuits in air

The table below lists some common simplified formulas for calculating the approximate inductance of several inductor constructions.

2.4.8 See also

- Gyrator – a network element that can simulate an inductor
- Induction coil
- Induction cooking
- Induction loop
- RL circuit
- RLC circuit
- Magnetomotive force
- Reactance (electronics) – opposition to a change of electric current or voltage
- Saturable reactor – a type of adjustable inductor
- Solenoid

2.4.9 Notes

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[18] Rosa 1908, equation (11a), subst. radius ρ = d/2 and cgs units

[19] Terman 1943, pp. 48–49, convert to natural logarithms and inches to mm.

[20] Terman (1943, p. 48) states for $l < 100\ d$, include $d/2l$ within the parentheses.

[21] ARRL Handbook, 66th Ed. American Radio Relay League (1989).

[22] Wheeler, H.A. (October 1928). "Simple Inductance Formulas for Radio Coils". *Proceedings of the Institute of Radio Engineers* **16** (10): 1398. Retrieved 22 June 2015.

[23] For the second formula, Terman 1943, p. 58 which cites to Wheeler 1928.

[24] Terman 1943, p. 58

[25] Terman 1943, p. 57

2.4.10 References

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2.4.11 External links

General

- How stuff works The initial concept, made very simple
- Capacitance and Inductance – A chapter from an online textbook
- Spiral inductor models. Article on inductor characteristics and modeling.
- Online coil inductance calculator. Online calculator calculates the inductance of conventional and toroidal coils using formulas 3, 4, 5, and 6, above.
- AC circuits
- Understanding coils and transforms
- Bowley, Roger (2009). "Inductor". *Sixty Symbols*. Brady Haran for the University of Nottingham.
- Inductors 101 Instructional Guide

2.5 Electrical impedance

Electrical impedance is the measure of the opposition that a circuit presents to a current when a voltage is applied.

In quantitative terms, it is the complex ratio of the voltage to the current in an alternating current (AC) circuit. Impedance extends the concept of resistance to AC circuits, and possesses both magnitude and phase, unlike resistance, which has only magnitude. When a circuit is driven with direct current (DC), there is no distinction between impedance and resistance; the latter can be thought of as impedance with zero phase angle.

It is necessary to introduce the concept of impedance in AC circuits because there are two additional impeding mechanisms to be taken into account besides the normal resistance of DC circuits: the induction of voltages in conductors self-induced by the magnetic fields of currents (inductance), and the electrostatic storage of charge induced by voltages between conductors (capacitance). The impedance caused by these two effects is collectively referred to as reactance and forms the imaginary part of complex impedance whereas resistance forms the real part.

The symbol for impedance is usually Z and it may be represented by writing its magnitude and phase in the form $|Z|\angle\theta$. However, cartesian complex number representation is often more powerful for circuit analysis purposes.

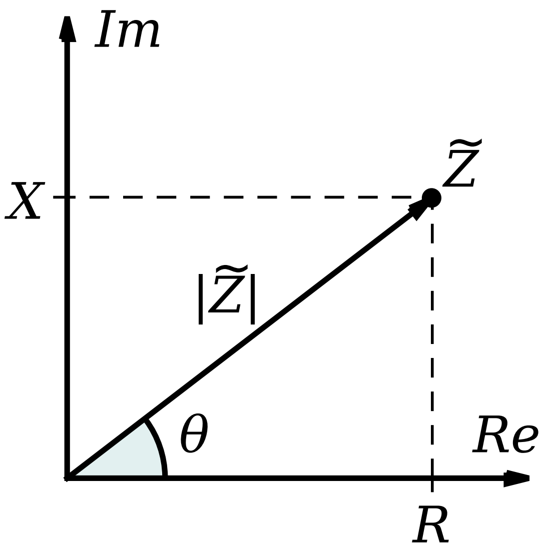
The term *impedance* was coined by Oliver Heaviside in July 1886.[1][2] Arthur Kennelly was the first to represent impedance with complex numbers in 1893.[3]

Impedance is defined as the frequency domain ratio of the voltage to the current.[4] In other words, it is the voltage–current ratio for a single complex exponential at a particular frequency ω. In general, impedance will be a complex number, with the same units as resistance, for which the SI unit is the ohm (Ω). For a sinusoidal current or voltage input, the polar form of the complex impedance relates the amplitude and phase of the voltage and current. In particular:

- The magnitude of the complex impedance is the ratio of the voltage amplitude to the current amplitude.
- The phase of the complex impedance is the phase shift by which the current lags the voltage.

The reciprocal of impedance is admittance (i.e., admittance is the current-to-voltage ratio, and it conventionally carries units of siemens, formerly called mhos).

2.5.1 Complex impedance



A graphical representation of the complex impedance plane

Impedance is represented as a complex quantity Z and the term *complex impedance* may be used interchangeably.

The polar form conveniently captures both magnitude and phase characteristics as

$$Z = |Z|e^{j\arg(Z)}$$

where the magnitude $|Z|$ represents the ratio of the voltage difference amplitude to the current amplitude, while the argument $\arg(Z)$ (commonly given the symbol θ) gives the phase difference between voltage and current. j is the imaginary unit, and is used instead of i in this context to avoid confusion with the symbol for electric current.

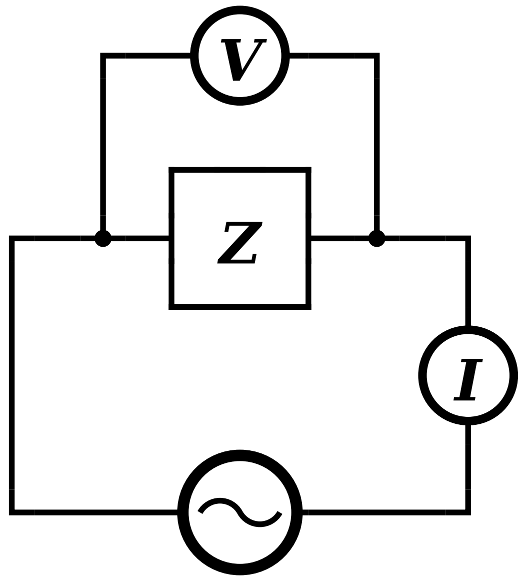
In Cartesian form, impedance is defined as

$$Z = R + jX$$

where the real part of impedance is the resistance R and the imaginary part is the reactance X .

Where it is needed to add or subtract impedances, the cartesian form is more convenient; but when quantities are multiplied or divided, the calculation becomes simpler if the polar form is used. A circuit calculation, such as finding the total impedance of two impedances in parallel, may require conversion between forms several times during the calculation. Conversion between the forms follows the normal conversion rules of complex numbers.

2.5.2 Ohm's law



An AC supply applying a voltage V , across a load Z , driving a current I .

Main article: Ohm's law

The meaning of electrical impedance can be understood by substituting it into Ohm's law.[5][6]

$$V = IZ = I|Z|e^{j\arg(Z)}$$

The magnitude of the impedance $|Z|$ acts just like resistance, giving the drop in voltage amplitude across an impedance Z for a given current I . The phase factor tells us that the current lags the voltage by a phase of $\theta = \arg(Z)$ (i.e., in the time domain, the current signal is shifted $\frac{\theta}{2\pi}T$ later with respect to the voltage signal).

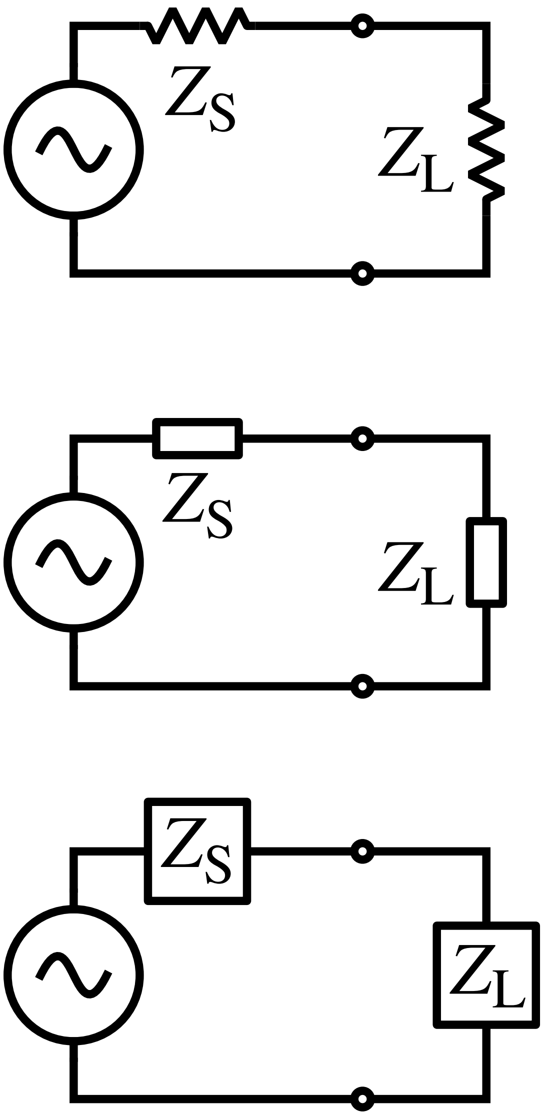
Just as impedance extends Ohm's law to cover AC circuits, other results from DC circuit analysis, such as voltage division, current division, Thévenin's theorem and Norton's theorem, can also be extended to AC circuits by replacing resistance with impedance.

2.5.3 Complex voltage and current

In order to simplify calculations, sinusoidal voltage and current waves are commonly represented as complex-valued functions of time denoted as V and I .[7][8]

$$V = |V|e^{j(\omega t + \phi_V)}$$
$$I = |I|e^{j(\omega t + \phi_I)}$$

Impedance is defined as the ratio of these quantities.



Generalized impedances in a circuit can be drawn with the same symbol as a resistor (US ANSI or DIN Euro) or with a labeled box.

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

Substituting these into Ohm's law, we have

$$\begin{aligned}|V|e^{j(\omega t+\phi_V)} &= |I|e^{j(\omega t+\phi_I)}|Z|e^{j\theta} \\ &= |I||Z|e^{j(\omega t+\phi_I+\theta)}\end{aligned}$$

Noting that this must hold for all t , we may equate the magnitudes and phases to obtain

$$\begin{aligned}|V| &= |I||Z| \\ \phi_V &= \phi_I + \theta\end{aligned}$$

The magnitude equation is the familiar Ohm's law applied to the voltage and current amplitudes, while the second equation defines the phase relationship.

Validity of complex representation

This representation using complex exponentials may be justified by noting that (by Euler's formula):

$$\cos(\omega t + \phi) = \frac{1}{2}\Big[e^{j(\omega t+\phi)} + e^{-j(\omega t+\phi)}\Big]$$

The real-valued sinusoidal function representing either voltage or current may be broken into two complex-valued functions. By the principle of superposition, we may analyse the behaviour of the sinusoid on the left-hand side by analysing the behaviour of the two complex terms on the right-hand side. Given the symmetry, we only need to perform the analysis for one right-hand term; the results will be identical for the other. At the end of any calculation, we may return to real-valued sinusoids by further noting that

$$\cos(\omega t + \phi) = \Re\Big\{e^{j(\omega t+\phi)}\Big\}$$

Phasors

Main article: Phasor (electronics)

A phasor is a constant complex number, usually expressed in exponential form, representing the complex amplitude (magnitude and phase) of a sinusoidal function of time. Phasors are used by electrical engineers to simplify computations involving sinusoids, where they can often reduce a differential equation problem to an algebraic one.

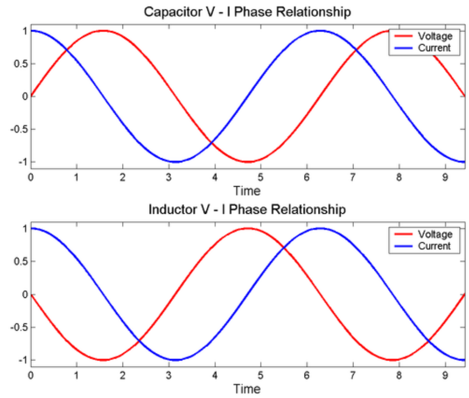
The impedance of a circuit element can be defined as the ratio of the phasor voltage across the element to the phasor current through the element, as determined by the relative amplitudes and phases of the voltage and current. This is identical to the definition from Ohm's law given above, recognising that the factors of $e^{j\omega t}$ cancel.

2.5.4 Device examples

The impedance of an ideal resistor is purely real and is referred to as a *resistive impedance*:

$$Z_R = R$$

In this case, the voltage and current waveforms are proportional and in phase.



The phase angles in the equations for the impedance of capacitors and inductors indicate that the voltage across a capacitor lags *the current through it by a phase of* $\pi/2$ *, while the voltage across an inductor* leads *the current through it by* $\pi/2$ *. The identical voltage and current amplitudes indicate that the magnitude of the impedance is equal to one.*

Ideal inductors and capacitors have a purely imaginary *reactive impedance*:

the impedance of inductors increases as frequency increases;

$$Z_L = j\omega L$$

the impedance of capacitors decreases as frequency increases;

$$Z_C = \frac{1}{j\omega C}$$

In both cases, for an applied sinusoidal voltage, the resulting current is also sinusoidal, but in quadrature, 90 degrees out of phase with the voltage. However, the phases have opposite signs: in an inductor, the current is *lagging*; in a capacitor the current is *leading*.

Note the following identities for the imaginary unit and its reciprocal:

$$j \equiv \cos\left(\frac{\pi}{2}\right) + j\sin\left(\frac{\pi}{2}\right) \equiv e^{j\frac{\pi}{2}}$$

$$\frac{1}{j} \equiv -j \equiv \cos\left(-\frac{\pi}{2}\right) + j\sin\left(-\frac{\pi}{2}\right) \equiv e^{j(-\frac{\pi}{2})}$$

Thus the inductor and capacitor impedance equations can be rewritten in polar form:

$$Z_L = \omega L e^{j\frac{\pi}{2}}$$

$$Z_C = \frac{1}{\omega C} e^{j(-\frac{\pi}{2})}$$

The magnitude gives the change in voltage amplitude for a given current amplitude through the impedance, while the exponential factors give the phase relationship.

Deriving the device-specific impedances

What follows below is a derivation of impedance for each of the three basic circuit elements: the resistor, the capacitor, and the inductor. Although the idea can be extended to define the relationship between the voltage and current of any arbitrary signal, these derivations will assume sinusoidal signals, since any arbitrary signal can be approximated as a sum of sinusoids through Fourier analysis.

Resistor For a resistor, there is the relation

$$v_{\text{R}}(t) = i_{\text{R}}(t)R$$

which is Ohm's law.

Considering the voltage signal to be

$$v_{\text{R}}(t) = V_p \sin(\omega t)$$

it follows that

$$\frac{v_{\text{R}}(t)}{i_{\text{R}}(t)} = \frac{V_p \sin(\omega t)}{I_p \sin(\omega t)} = R$$

This says that the ratio of AC voltage amplitude to alternating current (AC) amplitude across a resistor is R , and that the AC voltage leads the current across a resistor by 0 degrees.

This result is commonly expressed as

$$Z_{\text{resistor}} = R$$

Capacitor For a capacitor, there is the relation:

$$i_{\text{C}}(t) = C\frac{\mathrm{d}\, v_{\text{C}}(t)}{\mathrm{d}\, t}$$

Considering the voltage signal to be

$$v_{\text{C}}(t) = V_p \sin(\omega t)$$

it follows that

$$\frac{\mathrm{d}\, v_{\text{C}}(t)}{\mathrm{d}\, t} = \omega V_p \cos(\omega t)$$

and thus

$$\frac{v_{\text{C}}(t)}{i_{\text{C}}(t)} = \frac{V_p \sin(\omega t)}{\omega V_p C \cos(\omega t)} = \frac{\sin(\omega t)}{\omega C \sin\left(\omega t + \frac{\pi}{2}\right)}$$

This says that the ratio of AC voltage amplitude to AC current amplitude across a capacitor is $\frac{1}{\omega C}$, and that the AC voltage lags the AC current across a capacitor by 90 degrees (or the AC current leads the AC voltage across a capacitor by 90 degrees).

This result is commonly expressed in polar form as

$$Z_{\text{capacitor}} = \frac{1}{\omega C} e^{-j\frac{\pi}{2}}$$

or, by applying Euler's formula, as

$$Z_{\text{capacitor}} = -j\frac{1}{\omega C} = \frac{1}{j\omega C}$$

Inductor For the inductor, we have the relation:

$$v_{\text{L}}(t) = L\frac{\mathrm{d}\, i_{\text{L}}(t)}{\mathrm{d}\, t}$$

This time, considering the current signal to be:

$$i_{\text{L}}(t) = I_p \sin(\omega t)$$

it follows that:

$$\frac{\mathrm{d}\, i_{\text{L}}(t)}{\mathrm{d}\, t} = \omega I_p \cos(\omega t)$$

and thus:

$$\frac{v_{\text{L}}(t)}{i_{\text{L}}(t)} = \frac{\omega I_p L \cos(\omega t)}{I_p \sin(\omega t)} = \frac{\omega L \sin\left(\omega t + \frac{\pi}{2}\right)}{\sin(\omega t)}$$

This says that the ratio of AC voltage amplitude to AC current amplitude across an inductor is ωL , and that the AC voltage leads the AC current across an inductor by 90 degrees.

This result is commonly expressed in polar form as

$$Z_{\text{inductor}} = \omega L e^{j\frac{\pi}{2}}$$

or, using Euler's formula, as

$$Z_{\text{inductor}} = j\omega L$$

2.5.5 Generalised s-plane impedance

Impedance defined in terms of $j\omega$ can strictly be applied only to circuits that are driven with a steady-state AC signal. The concept of impedance can be extended to a circuit energised with any arbitrary signal by using complex frequency instead of $j\omega$. Complex frequency is given the symbol s and is, in general, a complex number. Signals are expressed in terms of complex frequency by taking the Laplace transform of the time domain expression of the signal. The impedance of the basic circuit elements in this more general notation is as follows:

For a DC circuit, this simplifies to $s = 0$. For a steady-state sinusoidal AC signal $s = j\omega$.

2.5.6 Resistance vs reactance

Resistance and reactance together determine the magnitude and phase of the impedance through the following relations:

$$|Z| = \sqrt{ZZ^*} = \sqrt{R^2 + X^2}$$
$$\theta = \arctan\left(\frac{X}{R}\right)$$

In many applications, the relative phase of the voltage and current is not critical so only the magnitude of the impedance is significant.

Resistance

Main article: Electrical resistance

Resistance R is the real part of impedance; a device with a purely resistive impedance exhibits no phase shift between the voltage and current.

$$R = |Z| \cos\theta$$

Reactance

Main article: Electrical reactance

Reactance X is the imaginary part of the impedance; a component with a finite reactance induces a phase shift θ between the voltage across it and the current through it.

$$X = |Z| \sin\theta$$

A purely reactive component is distinguished by the sinusoidal voltage across the component being in quadrature with the sinusoidal current through the component. This implies that the component alternately absorbs energy from the circuit and then returns energy to the circuit. A pure reactance will not dissipate any power.

Capacitive reactance Main article: Capacitance

A capacitor has a purely reactive impedance which is inversely proportional to the signal frequency. A capacitor consists of two conductors separated by an insulator, also known as a dielectric.

$$X_C = (\omega C)^{-1} = (2\pi f C)^{-1}$$

At low frequencies, a capacitor is an open circuit so no charge flows in the dielectric.

A DC voltage applied across a capacitor causes charge to accumulate on one side; the electric field due to the accumulated charge is the source of the opposition to the current. When the potential associated with the charge exactly balances the applied voltage, the current goes to zero.

Driven by an AC supply, a capacitor will only accumulate a limited amount of charge before the potential difference changes sign and the charge dissipates. The higher the frequency, the less charge will accumulate and the smaller the opposition to the current.

Inductive reactance Main article: Inductance

Inductive reactance X_L is proportional to the signal frequency f and the inductance L.

$$X_L = \omega L = 2\pi f L$$

An inductor consists of a coiled conductor. Faraday's law of electromagnetic induction gives the back emf $\mathcal{E}$ (voltage opposing current) due to a rate-of-change of magnetic flux density B through a current loop.

$$\mathcal{E} = -\frac{d\Phi_B}{dt}$$

For an inductor consisting of a coil with N loops this gives.

$$\mathcal{E} = -N\frac{d\Phi_B}{dt}$$

The back-emf is the source of the opposition to current flow. A constant direct current has a zero rate-of-change, and sees an inductor as a short-circuit (it is typically made from a material with a low resistivity). An alternating current has a time-averaged rate-of-change that is proportional to frequency, this causes the increase in inductive reactance with frequency.

Total reactance The total reactance is given by

$$X = X_L - X_C$$

so that the total impedance is

$$Z = R + jX$$

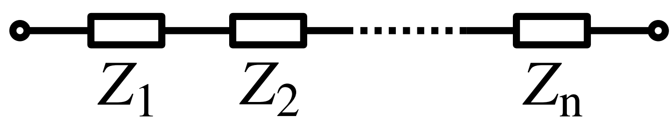
2.5.7 Combining impedances

Main article: Series and parallel circuits

The total impedance of many simple networks of components can be calculated using the rules for combining impedances in series and parallel. The rules are identical to those used for combining resistances, except that the numbers in general will be complex numbers. In the general case, however, equivalent impedance transforms in addition to series and parallel will be required.

Series combination

For components connected in series, the current through each circuit element is the same; the total impedance is the sum of the component impedances.



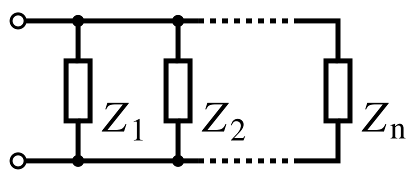
$$Z_{\text{eq}} = Z_1 + Z_2 + \cdots + Z_n$$

Or explicitly in real and imaginary terms:

$$Z_{\text{eq}} = R + jX = (R_1 + R_2 + \cdots + R_n) + j(X_1 + X_2 + \cdots + X_n)$$

Parallel combination

For components connected in parallel, the voltage across each circuit element is the same; the ratio of currents through any two elements is the inverse ratio of their impedances.



Hence the inverse total impedance is the sum of the inverses of the component impedances:

$$\frac{1}{Z_{\text{eq}}} = \frac{1}{Z_1} + \frac{1}{Z_2} + \cdots + \frac{1}{Z_n}$$

or, when n = 2:

$$\frac{1}{Z_{\text{eq}}} = \frac{1}{Z_1} + \frac{1}{Z_2} = \frac{Z_1 + Z_2}{Z_1 Z_2}$$

$$Z_{\text{eq}} = \frac{Z_1 Z_2}{Z_1 + Z_2}$$

The equivalent impedance Z_{eq} can be calculated in terms of the equivalent series resistance R_{eq} and reactance X_{eq}.[9]

$$Z_{\text{eq}} = R_{\text{eq}} + jX_{\text{eq}}$$

$$R_{\text{eq}} = \frac{(X_1 R_2 + X_2 R_1)(X_1 + X_2) + (R_1 R_2 - X_1 X_2)(R_1 + R_2)}{(R_1 + R_2)^2 + (X_1 + X_2)^2}$$

$$X_{\text{eq}} = \frac{(X_1 R_2 + X_2 R_1)(R_1 + R_2) - (R_1 R_2 - X_1 X_2)(X_1 + X_2)}{(R_1 + R_2)^2 + (X_1 + X_2)^2}$$

2.5.8 Measurement

The measurement of the impedance of devices and transmission lines is a practical problem in radio technology and other fields. Measurements of impedance may be carried out at one frequency, or the variation of device impedance over a range of frequencies may be of interest. The impedance may be measured or displayed directly in ohms, or other values related to impedance may be displayed; for example, in a radio antenna, the standing wave ratio or reflection coefficient may be more useful than the impedance alone. The measurement of impedance requires the measurement of the magnitude of voltage and current, and the phase difference between them. Impedance is often measured by "bridge" methods, similar to the direct-current Wheatstone bridge; a calibrated reference impedance is adjusted to balance off the effect of the impedance of the device under test. Impedance measurement in power electronic devices may require simultaneous measurement and provision of power to the operating device.

The impedance of a device can be calculated by complex division of the voltage and current. The impedance of the device can be calculated by applying a sinusoidal voltage to the device in series with a resistor, and measuring the voltage across the resistor and across the device. Performing this measurement by sweeping the frequencies of the applied signal provides the impedance phase and magnitude.[10]

The use of an impulse response may be used in combination with the fast Fourier transform (FFT) to rapidly measure the electrical impedance of various electrical devices.[10]

The LCR meter (Inductance (L), Capacitance (C), and Resistance (R)) is a device commonly used to measure the inductance, resistance and capacitance of a component; from these values, the impedance at any frequency can be calculated.

2.5.9 Variable impedance

In general, neither impedance nor admittance can be time varying as they are defined for complex exponentials for $-\infty < t < +\infty$. If the complex exponential voltage–current ratio changes over time or amplitude, the circuit element cannot be described using the frequency domain. However, many systems (e.g., varicaps that are used in radio tuners) may exhibit non-linear or time-varying voltage–current ratios that appear to be linear time-invariant (LTI) for small signals over small observation windows; hence, they can be roughly described as having a time-varying impedance. That is, this description is an approximation; over large signal swings or observation windows, the voltage–current relationship is non-LTI and cannot be described by impedance.

2.5.10 See also

- Bioelectrical impedance analysis
- Characteristic impedance
- Electrical characteristics of dynamic loudspeakers
- High impedance
- Immittance
- Impedance bridging
- Impedance cardiography
- Impedance matching
- Impedance microbiology
- Negative impedance converter
- Resistance distance
- Impedance control

2.5.11 References

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2.5.12 External links

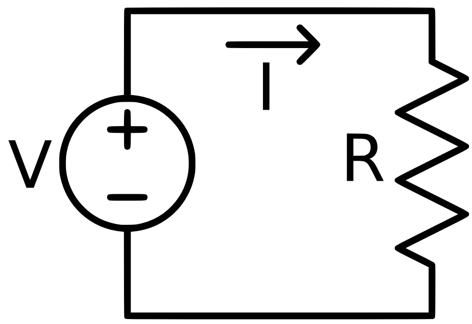
- Explaining Impedance
- Antenna Impedance
- ECE 209: Review of Circuits as LTI Systems – Brief explanation of Laplace-domain circuit analysis; includes a definition of impedance.

2.6 Voltage source

A **voltage source** is a two terminal device which can maintain a fixed voltage.[1] An ideal voltage source can maintain the fixed voltage independent of the load resistance or the output current. However, a real-world voltage source cannot supply unlimited current. A voltage source is the dual of a current source. Real-world sources of electrical energy, such as batteries, generators, and power systems, can be modeled for analysis purposes as a combination of an ideal voltage source and additional combinations of impedance elements.

2.6.1 Ideal voltage sources

An **ideal voltage source** is a two-terminal device that maintains a fixed voltage drop across its terminals. It is often used as a mathematical abstraction that simplifies the analysis of real electric circuits. If the voltage across an ideal voltage source can be specified independently of any other variable in a circuit, it is called an **independent** voltage source. Conversely, if the voltage across an



A schematic diagram of a real voltage source, V*, driving a resistor,* R*, and creating a current* I

ideal voltage source is determined by some other voltage or current in a circuit, it is called a **dependent** or **controlled voltage source**. A mathematical model of an amplifier will include dependent voltage sources whose magnitude is governed by some fixed relation to an input signal, for example.[2] In the analysis of faults on electrical power systems, the whole network of interconnected sources and transmission lines can be usefully replaced by an ideal (AC) voltage source and a single equivalent impedance.

Symbols used for voltage sources

The internal resistance of an ideal voltage source is zero; it is able to supply or absorb any amount of current. The current through an ideal voltage source is completely determined by the external circuit. When connected to an open circuit, there is zero current and thus zero power. When connected to a load resistance, the current through the source approaches infinity as the load resistance approaches zero (a short circuit). Thus, an ideal voltage source can supply unlimited power.

No real voltage source is ideal; all have a non-zero effective internal resistance, and none can supply unlimited current. However, the internal resistance of a real voltage source is effectively modeled in linear circuit analysis by combining a non-zero resistance in series with an ideal voltage source (a Thévenin equivalent circuit).

2.6.2 Comparison between voltage and current sources

Most sources of electrical energy (the mains, a battery) are modeled as voltage sources. An *ideal* voltage source provides no energy when it is loaded by an open circuit (i.e. an infinite impedance), but approaches infinite energy and current when the load resistance approaches zero (a short circuit). Such a theoretical device would have a zero ohm output impedance in series with the source. A real-world voltage source has a very low, but non-zero internal resistance & output impedance: often much less than 1 ohm.

Conversely, a current source provides a constant current, as long as the load connected to the source terminals has sufficiently low impedance. An ideal current source would provide no energy to a short circuit and approach infinite energy and voltage as the load resistance approaches infinity (an open circuit). An *ideal* current source has an infinite output impedance in parallel with the source. A *real-world* current source has a very high, but finite output impedance. In the case of transistor current sources, impedance of a few megohms (at low frequencies) is typical.

Since no ideal sources of either variety exist (all real-world examples have finite and non-zero source impedance), any current source can be considered as a voltage source with the *same* source impedance and vice versa. Voltage sources and current sources are sometimes said to be duals of each other and any non ideal source can be converted from the one to the other by applying Norton's or Thévenin's theorems.

2.6.3 References and notes

[1] An introduction to electronics

[2] K. C. A. Smith, R. E. Alley , *Electrical circuits: an introduction*, Cambridge University Press, 1992 ISBN 0-521-37769-2, pp. 11-13

2.6.4 See also

- Bandgap voltage reference
- Voltage divider
- Voltage reference
- Voltage regulator

2.7 Current source

A **current source** is an electronic circuit that delivers or absorbs an electric current which is independent of the voltage across it.

A current source is the dual of a voltage source. The term constant-current 'sink' is sometimes used for sources fed from a negative voltage supply. Figure 1 shows the schematic symbol for an ideal current source, driving a resistor load. There are two types. An **independent current source** (or sink) delivers a constant current. A **dependent current source** delivers a current which is proportional to some other voltage or current in the circuit.

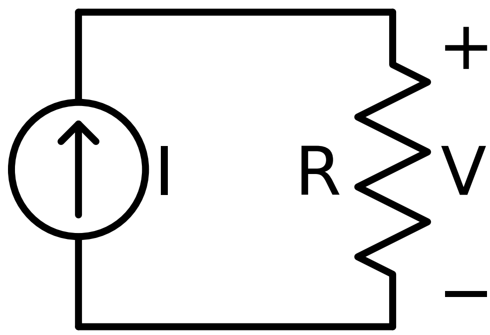


Figure 1: An ideal current source, I*, driving a resistor,* R*, and creating a voltage* V

2.7.1 Background

Figure 2: Source symbols

In circuit theory, an **ideal current source** is a circuit element where the current through it is independent of the voltage across it. It is a mathematical model, which real devices can only approach in performance. If the current through an ideal current source can be specified independently of any other variable in a circuit, it is called an *independent* current source. Conversely, if the current through an ideal current source is determined by some other voltage or current in a circuit, it is called a **dependent** or **controlled current source**. Symbols for these sources are shown in Figure 2.

The internal resistance of an ideal current source is infinite. An independent current source with zero current is identical to an ideal open circuit. The voltage across an ideal current source is completely determined by the circuit it is connected to. When connected to a short circuit, there is zero voltage and thus zero power delivered. When connected to a load resistance, the voltage across the source approaches infinity as the load resistance approaches infinity (an open circuit). Thus, an ideal current source, if such a thing existed in reality, could supply unlimited power and so would represent an unlimited source of energy.

No physical current source is ideal. For example, no physical current source can operate when applied to an open circuit. There are two characteristics that define a current source in real life. One is its internal resistance and the other is its compliance voltage. The compliance voltage is the maximum voltage that the current source can supply to a load. Over a given load range, it is possible for some types of real current sources to exhibit nearly infinite internal resistance. However, when the current source reaches its compliance voltage, it abruptly stops being a current source.

In circuit analysis, a current source having finite internal resistance is modeled by placing the value of that resistance across an ideal current source (the Norton equivalent circuit). However, this model is only useful when a current source is operating within its compliance voltage.

2.7.2 Implementations

Passive current source

The simplest non-ideal current source consists of a voltage source in series with a resistor. The amount of current available from such a source is given by the ratio of the voltage across the voltage source to the resistance of the resistor (Ohm's law; I = V/R). This value of current will only be delivered to a load with zero voltage drop across its terminals (a short circuit, an uncharged capacitor, a charged inductor, a virtual ground circuit, etc.) The current delivered to a load with nonzero voltage (drop) across its terminals (a linear or nonlinear resistor with a finite resistance, a charged capacitor, an uncharged inductor, a voltage source, etc.) will always be different. It is given by the ratio of the voltage drop across the resistor (the difference between the exciting voltage and the voltage across the load) to its resistance. For a nearly ideal current source, the value of the resistor should be very large but this implies that, for a specified current, the voltage source must be very large (in the limit as the resistance and the voltage go to infinity, the current source will become ideal and the current will not depend at all on the voltage across the load). Thus, efficiency is low (due to power loss in the resistor) and it is usually impractical to construct a 'good' current source this way. Nonetheless, it is often the case that such a circuit will provide adequate performance when the specified current and load resistance are small. For example, a 5 V voltage source in series with a 4.7 kilohm resistor will provide an *approximately* constant current of 1 mA (±5%) to a load resistance in the range of 50 to 450 ohm.

A Van de Graaff generator is an example of such a high voltage current source. It behaves as an almost constant current source because of its very high output voltage coupled with its very high output resistance and so it supplies the same few microamperes at any output voltage up to hundreds of thousands of volts (or even tens of megavolts) for large laboratory versions.

Active current sources without negative feedback

In these circuits, the output current is not monitored and controlled by means of negative feedback.

Current-stable nonlinear implementation They are implemented by active electronic components (transistors) having current-stable nonlinear output characteristic when driven by steady input quantity (current or voltage). These circuits behave as dynamic resistors changing its present resistance to compensate current variations. For example, if the load increases its resistance, the transistor decreases its present output resistance (and *vice versa*) to keep up a constant total resistance in the circuit.

Active current sources have many important applications in electronic circuits. They are often used in place of ohmic resistors in analog integrated circuits (e.g., a differential amplifier) to generate a current that depends slightly on the voltage across the load.

The common emitter configuration driven by a constant input current or voltage and common source (common cathode) driven by a constant voltage naturally behave as current sources (or sinks) because the output impedance of these devices is naturally high. The output part of the simple current mirror is an example of such a current source widely used in integrated circuits. The common base, common gate and common grid configurations can serve as constant current sources as well.

A JFET can be made to act as a current source by tying its gate to its source. The current then flowing is the IDSS of the FET. These can be purchased with this connection already made and in this case the devices are called current regulator diodes or constant current diodes or current limiting diodes (CLD). An enhancement mode N channel MOSFET can be used in the circuits listed below.

Following voltage implementation An example: bootstrapped current source.[1]

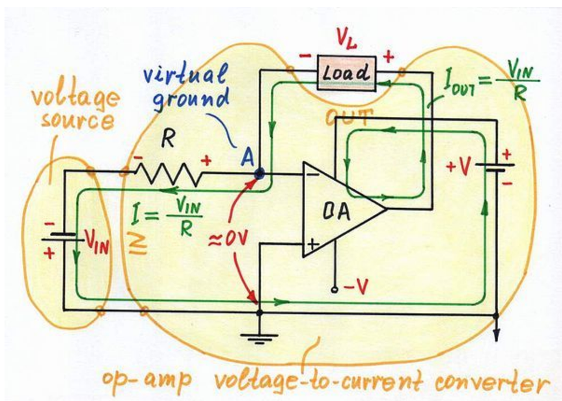


Figure 3: In an op-amp voltage-controlled current source *the op-amp compensates the voltage drop across the load by adding the same voltage to the exciting input voltage.*

Voltage compensation implementation The simple resistor current source will become "ideal" if the voltage across the load is somehow held zero. This idea seems paradoxical since real loads always "create" voltage drops across themselves but it is yet implemented by applying a parallel negative feedback. In these circuits, an op-amp compensates the voltage drop across the load by adding the same voltage to the exciting input voltage. As a result, the op-amp inverting input is held at virtual ground and the combination of the input voltage source, the resistor and the supplied op-amp constitutes an “ideal” current source with value *I*OUT = *V*IN/*R*. The op-amp voltage-to-current converter in Figure 3, a transimpedance amplifier and an op-amp inverting amplifier are typical implementations of this idea.

The floating load is a serious disadvantage of this circuit solution.

Current compensation implementation A typical example are Howland current source[2] and its derivative Deboo integrator.[3] In the last example (see Fig. 1 there), the Howland current source consists of an input voltage source VIN, a positive resistor R, a load (the capacitor C acting as impedance *Z*) and a negative impedance converter INIC ($R_1 = R_2 = R_3 = R$ and the op-amp). The input voltage source and the resistor R constitute an imperfect current source passing current *IR* through the load (see Fig. 3 in the source). The INIC acts as a second current source passing “helping” current *I-R* through the load. As a result, the total current flowing through the load is constant and the circuit impedance seen by the input source is increased. However the Howland current source isn't widely used because it requires the four resistors to be perfectly matched, and its impedance drops at high frequencies.[4]

The grounded load is an advantage of this circuit solution.

Current sources with negative feedback

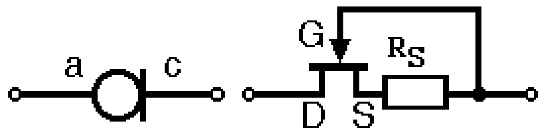
They are implemented as a voltage follower with series negative feedback driven by a constant input voltage source (i.e., a *negative feedback voltage stabilizer*). The voltage follower is loaded by a constant (current sensing) resistor acting as a simple current-to-voltage converter connected in the feedback loop. The external load of this current source is connected somewhere in the path of the current supplying the current sensing resistor but out of the feedback loop.

The voltage follower adjusts its output current *I*OUT flowing through the load so that to make the voltage drop *V*R = *I*OUT*R* across the current sensing resistor R equal to the constant input voltage *V*IN. Thus the voltage stabilizer keeps up a constant voltage drop across a constant resistor; so, a constant current *I*OUT = *V*R/*R* = *V*IN/*R* flows through the resistor and respectively through the load.

If the input voltage varies, this arrangement will act as a voltage-to-current converter (voltage-controlled current source, VCCS); it can be thought as a reversed (by means of negative feedback) current-to-voltage converter. The resistance R determines the transfer ratio (transconductance).

Current sources implemented as circuits with series negative feedback have the disadvantage that the voltage drop across the current sensing resistor decreases the maximal voltage across the load (the *compliance voltage*).

Simple transistor current sources



Circuit

Constant current diode The simplest constant-current source or sink is formed from one component: a JFET with its gate attached to its source. Once the drain-source voltage reaches a certain minimum value, the JFET enters saturation where current is approximately constant. This configuration is known as a constant-current diode, as it behaves much like a dual to the constant voltage diode (Zener diode) used in simple voltage sources.

Due to the large variability in saturation current of JFETs, it is common to also include a source resistor (shown in the image to the right) which allows the current to be tuned down to a desired value.

Zener diode current source In this bipolar junction transistor (BJT) implementation (Figure 4) of the general idea above, a *Zener voltage stabilizer* (R1 and DZ1) drives an *emitter follower* (Q1) loaded by a *constant emitter resistor* (R2) sensing the load current. The external (floating) load of this current source is connected to the collector so that almost the same current flows through it and the emitter resistor (they can be thought of as connected in series). The transistor Q1 adjusts the output (collector) current so as to keep the voltage drop across the constant emitter resistor, R2, almost equal to the relatively constant voltage drop across the Zener diode DZ1. As a result, the output current is almost constant even if the load resistance and/or voltage vary. The operation of the circuit is considered in details below.

A Zener diode, when reverse biased (as shown in the circuit) has a constant voltage drop across it irrespective of the current flowing through it. Thus, as long as the Zener current (*I*Z) is above a certain level (called holding current), the voltage across the Zener diode (*V*Z) will be constant. Resistor, R1, supplies the Zener current and the base current (*I*B) of NPN transistor (Q1). The constant Zener voltage is applied across the base of Q1 and emitter resistor, R2.

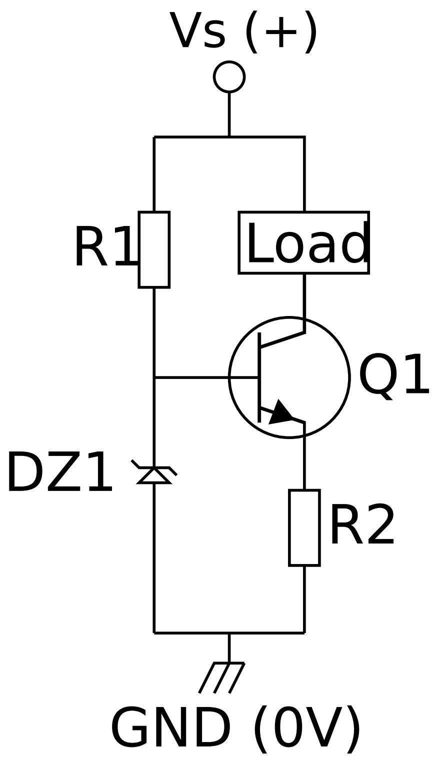


Figure 4: Typical BJT constant current source with negative feedback

Voltage across R2 (VR$_2$) is given by VZ − VBE, where VBE is the base-emitter drop of Q1. The emitter current of Q1 which is also the current through R2 is given by

$$I_{R2}(=I_E=I_C)=\frac{V_{R2}}{R_{R2}}=\frac{V_Z-V_{BE}}{R_{R2}}.$$

Since VZ is constant and VBE is also (approximately) constant for a given temperature, it follows that VR$_2$ is constant and hence IE is also constant. Due to transistor action, emitter current, IE, is very nearly equal to the collector current, IC, of the transistor (which in turn, is the current through the load). Thus, the load current is constant (neglecting the output resistance of the transistor due to the Early effect) and the circuit operates as a constant current source. As long as the temperature remains constant (or doesn't vary much), the load current will be independent of the supply voltage, R1 and the transistor's gain. R2 allows the load current to be set at any desirable value and is calculated by

$$R_{R2}=\frac{V_Z-V_{BE}}{I_{R2}}$$

or

$$R_{R2}=\frac{V_Z-0.65}{I_{R2}}$$

since VBE is typically 0.65 V for a silicon device.[5]

(IR$_2$ is also the emitter current and is assumed to be the same as the collector or required load current, provided hFE is sufficiently large). Resistance, RR$_1$, at resistor R1 is calculated as

$$R_{R1}=\frac{V_S-V_Z}{I_Z+K\cdot I_B}$$

where K = 1.2 to 2 (so that R_1 is low enough to ensure adequate IB),

$$I_B=\frac{I_C}{h_{FE,\mathrm{min}}}$$

and hFE,$_{\mathrm{min}}$ is the lowest acceptable current gain for the particular transistor type being used.

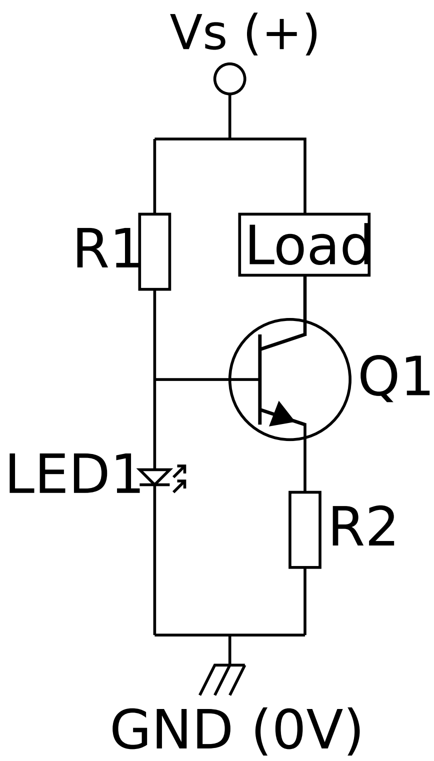


Figure 5: Typical constant current source (CCS) using LED instead of Zener diode

LED current source The Zener diode can be replaced by any other diode; e.g., a light-emitting diode LED1 as shown in Figure 5. The LED voltage drop (VD) is now used to derive the constant voltage and also has the additional advantage of tracking (compensating) VBE changes due to temperature. R_2 is calculated as

$$R_2=\frac{V_D-V_{BE}}{I_{R2}}$$

and R_1 as

$R_1 = \frac{V_S - V_D}{I_D + K \cdot I_B}$, where *I*D is the LED current.

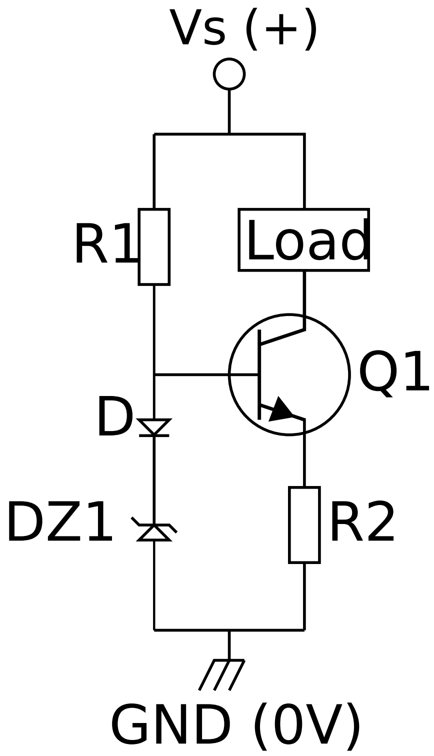


Figure 6: Typical constant current source (CCS) with diode compensation

Transistor current source with diode compensation Temperature changes will change the output current delivered by the circuit of Figure 4 because VBE is sensitive to temperature. Temperature dependence can be compensated using the circuit of Figure 6 that includes a standard diode D (of the same semiconductor material as the transistor) in series with the Zener diode as shown in the image on the left. The diode drop (*V*D) tracks the *V*BE changes due to temperature and thus significantly counteracts temperature dependence of the CCS.

Resistance R_2 is now calculated as

$$R_2 = \frac{V_Z + V_D - V_{BE}}{I_{R2}}$$

Since *V*D = *V*BE = 0.65 V,[6]

$$R_2 = \frac{V_Z}{I_{R2}}$$

(In practice, *V*D is never exactly equal to *V*BE and hence it only suppresses the change in *V*BE rather than nulling it out.)

R_1 is calculated as

$$R_1 = \frac{V_S - V_Z - V_D}{I_Z + K \cdot I_B}$$

(the compensating diode's forward voltage drop, *V*D, appears in the equation and is typically 0.65 V for silicon devices.[6])

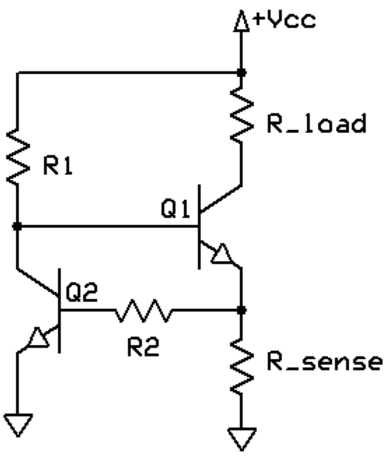
This method is most effective for Zener diodes rated at 5.6 V or more. For breakdown diodes of less than 5.6 V, the compensating diode is usually not required because the breakdown mechanism is not as temperature dependent as it is in breakdown diodes above this voltage.

Current mirror with emitter degeneration Series negative feedback is also used in the two-transistor current mirror with emitter degeneration. Negative feedback is a basic feature in some current mirrors using multiple transistors, such as the Widlar current source and the Wilson current source.

Constant current source with thermal compensation One limitation with the circuits in Figures 5 and 6 is that the thermal compensation is imperfect. In bipolar transistors, as the junction temperature increases the V_{be} drop (voltage drop from base to emitter) decreases. In the two previous circuits, a decrease in V_{be} will cause an increase in voltage across the emitter resistor, which in turn will cause an increase in collector current drawn through the load. The end result is that the amount of 'constant' current supplied is at least somewhat dependent on temperature. This effect is mitigated to a large extent, but not completely, by corresponding voltage drops for the diode, D1, in Figure 6, and the LED, LED1, in Figure 5. If the power dissipation in the active device of the CCS is not small and/or insufficient emitter degeneration is used, this can become a non-trivial issue.

Imagine in Figure 5, at power up, that the LED has 1 V across it driving the base of the transistor. At room temperature there is about 0.6 V drop across the V_{be} junction and hence 0.4 V across the emitter resistor, giving an approximate collector (load) current of $0.4/R_e$ amps. Now imagine that the power dissipation in the transistor causes it to heat up. This causes the V_{be} drop (which was 0.6 V at room temperature) to drop to, say, 0.2 V. Now the voltage across the emitter resistor is 0.8 V, twice what it was before the warmup. This means that the collector (load) current is now twice the design value! This is an extreme example of course, but serves to illustrate the issue.

The circuit to the left overcomes the thermal problem (see also, current limiting). To see how the circuit works, assume the voltage has just been applied at V+. Current runs through R1 to the base of Q1, turning it on and causing current to begin to flow through the load into the collector of Q1. This same load current then flows out of



Current limiter with NPN transistors

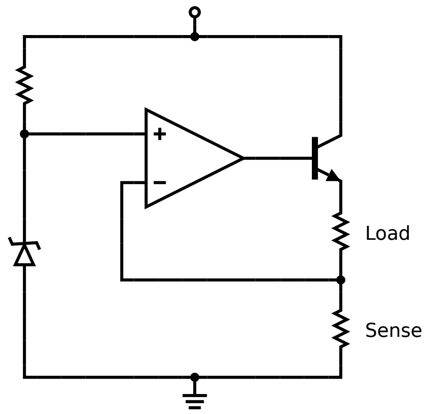


Figure 7: Typical op-amp current source.

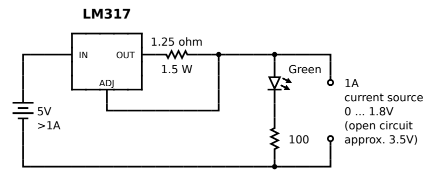


Figure 8: Constant current source using the LM317 voltage regulator

Q1's emitter and consequently through R_{sense} to ground. When this current through R_{sense} to ground is sufficient to cause a voltage drop that is equal to the V_{be} drop of Q2, Q2 begins to turn on. As Q2 turns on it pulls more current through its collector resistor, R1, which diverts some of the injected current in the base of Q1, causing Q1 to conduct less current through the load. This creates a negative feedback loop within the circuit, which keeps the voltage at Q1's emitter almost exactly equal to the V_{be} drop of Q2. Since Q2 is dissipating very little power compared to Q1 (since all the load current goes through Q1, not Q2), Q2 will not heat up any significant amount and the reference (current setting) voltage across R_{sense} will remain steady at ~0.6 V, or one diode drop above ground, regardless of the thermal changes in the V_{be} drop of Q1. The circuit is still sensitive to changes in the ambient temperature in which the device operates as the BE voltage drop in Q2 varies slightly with temperature.

Op-amp current sources The simple transistor current source from Figure 4 can be improved by inserting the base-emitter junction of the transistor in the feedback loop of an op-amp (Figure 7). Now the op-amp increases its output voltage to compensate for the VBE drop. The circuit is actually a buffered non-inverting amplifier driven by a constant input voltage. It keeps up this constant voltage across the constant sense resistor. As a result, the current flowing through the load is constant as well; it is exactly the Zener voltage divided by the sense resistor. The load can be connected either in the emitter (Figure 7) or in the collector (Figure 4) but in both the cases it is floating as in all the circuits above. The transistor is not needed if the required current doesn't exceed the sourcing ability of the op-amp. The article on current mirror discusses another example of these so-called *gain-boosted* current mirrors.

Voltage regulator current sources The general negative feedback arrangement can be implemented by an IC voltage regulator (LM317 voltage regulator on Figure 8). As with the bare emitter follower and the precise op-amp follower above, it keeps up a constant voltage drop (1.25 V) across a constant resistor (1.25 Ω); so, a constant current (1 A) flows through the resistor and the load. The LED is on when the voltage across the load exceeds 1.8 V (the indicator circuit introduces some error). The grounded load is an important advantage of this solution.

Curpistor tubes Nitrogen-filled glass tubes with two electrodes and a calibrated Becquerel (fissions per second) amount of ^{226}Ra offer a constant number of charge carriers per second for conduction, which determines the maximum current the tube can pass over a voltage range from 25 to 500 V.[7]

2.7.3 Current and voltage source comparison

Most sources of electrical energy (mains electricity, a battery, etc.) are best modeled as voltage sources. Such sources provide constant voltage, which means that as long as the current drawn from the source is within the source's capabilities, its output voltage stays constant. An ideal voltage source provides no energy when it is loaded by an open circuit (i.e. an infinite impedance), but approaches infinite power and current when the load resistance approaches zero (a short circuit). Such a theoretical device would have a zero ohm output impedance in series with the source. A real-world voltage source has a very low, but non-zero output impedance: often much less than 1 ohm.

Conversely, a current source provides a constant current, as long as the load connected to the source terminals has sufficiently low impedance. An ideal current source would provide no energy to a short circuit and approach infinite energy and voltage as the load resistance approaches infinity (an open circuit). An *ideal* current source has an infinite output impedance in parallel with the source. A *real-world* current source has a very high, but finite output impedance. In the case of transistor current sources, impedances of a few megohms (at DC) are typical.

An *ideal* current source cannot be connected to an *ideal* open circuit because this would create the paradox of running a constant, non-zero current (from the current source) through an element with a defined zero current (the open circuit). Also, a current source should not be connected to another current source if their currents differ but this arrangement is frequently used (e.g., in amplifying stages with dynamic load, CMOS circuits, etc.)

Similarly, an *ideal* voltage source cannot be connected to an *ideal* short circuit (R=0), since this would result a similar paradox of finite nonzero voltage across an element with defined zero voltage (the short circuit). Also, a voltage source should not be connected to another voltage source if their voltages differ but again this arrangement is frequently used (e.g., in common base and differential amplifying stages).

Contrary, current and voltage sources can be connected to each other without any problems, and this technique is widely used in circuitry (e.g., in cascode circuits, differential amplifier stages with common emitter current source, etc.)

Because no ideal sources of either variety exist (all real-world examples have finite and non-zero source impedance), any current source can be considered as a voltage source with the *same* source impedance and vice versa. These concepts are dealt with by Norton's and Thévenin's theorems.

2.7.4 See also

- Constant current
- Current limiting
- Current loop
- Current mirror
- Current sources and sinks
- Fontana bridge, a compensated current source
- Iron-hydrogen resistor
- Voltage-to-current converter
- Welding power supply, a device used for arc welding, many of which are designed as constant current devices.
- Widlar current source

2.7.5 References and notes

[1] Widlar bilateral current source

[2] "AN-1515 A Comprehensive Study of the Howland Current Pump" (PDF) (PDF). Texas Instruments, Inc. 2013 (2008). Check date values in: |date= (help)

[3] Consider the "Deboo" Single-Supply Integrator

[4] Horowitz, Paul; Winfield Hill (1989). *The Art of Electronics, 2nd Ed.* UK: Cambridge University Press. p. 182. ISBN 0521370957.

[5] The value for *VBE* varies logarithmically with current level: for more detail see diode modelling.

[6] See above note on logarithmic current dependence.

[7] "Tung-Sol: *Curpistor, minute current regulator* data sheet" (PDF). Retrieved 26 May 2013.

2.7.6 Further reading

- "Current Sources & Voltage References" Linden T. Harrison; Publ. Elsevier-Newnes 2005; 608-pages; ISBN 0-7506-7752-X

2.7.7 External links

- Tutorial video on how to build a constant current source using an LM317
- *Current Regulators*; Electrical Engineering Training Series
- 4QD-TEC: Electronics Circuits Reference Archive
- Differential amplifiers and current sources
- Article about current sources on ESP

Chapter 3

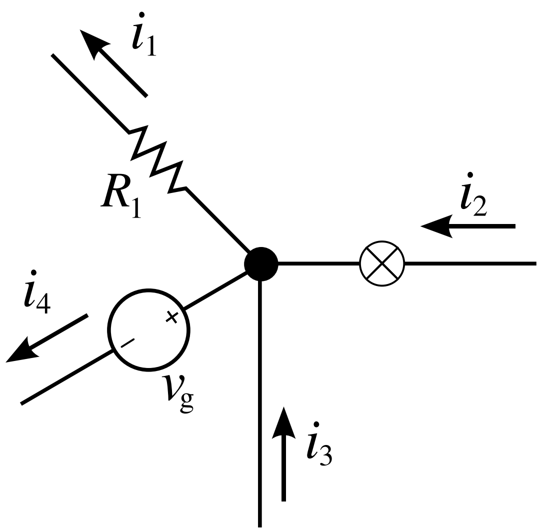
Basic circuit laws

3.1 Kirchhoff's circuit laws

Kirchhoff's circuit laws are two equalities that deal with the current and potential difference (commonly known as voltage) in the lumped element model of electrical circuits. They were first described in 1845 by German physicist Gustav Kirchhoff.[1] This generalized the work of Georg Ohm and preceded the work of Maxwell. Widely used in electrical engineering, they are also called **Kirchhoff's rules** or simply **Kirchhoff's laws**.

Both of Kirchhoff's laws can be understood as corollaries of the Maxwell equations in the low-frequency limit. They are accurate for DC circuits, and for AC circuits at frequencies where the wavelengths of electromagnetic radiation are very large compared to the circuits.

3.1.1 Kirchhoff's current law (KCL)



The current entering any junction is equal to the current leaving that junction. $i_2 + i_3 = i_1 + i_4$

This law is also called **Kirchhoff's first law**, **Kirchhoff's point rule**, or **Kirchhoff's junction rule** (or nodal rule).

The principle of conservation of electric charge implies that:

> At any node (junction) in an electrical circuit, the sum of currents flowing into that node is equal to the sum of currents flowing out of that node

or equivalently

> The algebraic sum of currents in a network of conductors meeting at a point is zero.

Recalling that current is a signed (positive or negative) quantity reflecting direction towards or away from a node, this principle can be stated as:

$$\sum_{k=1}^{n} I_k = 0$$

n is the total number of branches with currents flowing towards or away from the node.

This formula is valid for complex currents:

$$\sum_{k=1}^{n} \tilde{I}_k = 0$$

The law is based on the conservation of charge whereby the charge (measured in coulombs) is the product of the current (in amperes) and the time (in seconds).

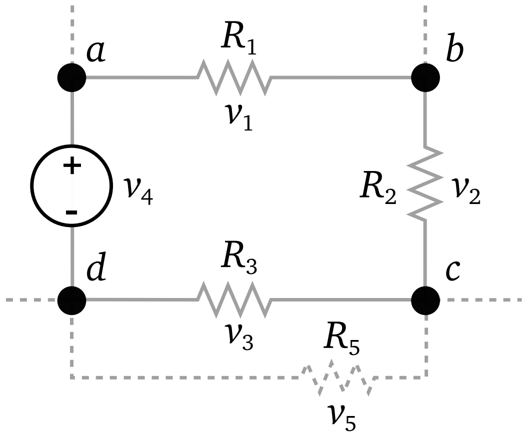
Uses

A matrix version of Kirchhoff's current law is the basis of most circuit simulation software, such as SPICE. Kirchhoff's current law combined with Ohm's Law is used in nodal analysis.

KCL is applicable to any lumped network irrespective of the nature of the network; whether unilateral or bilateral, active or passive, linear or non-linear.

3.1.2 Kirchhoff's voltage law (KVL)

This law is also called **Kirchhoff's second law**, **Kirchhoff's loop (or mesh) rule**, and **Kirchhoff's second rule**.



The sum of all the voltages around a loop is equal to zero.
$v_1 + v_2 + v_3 - v_4 = 0$

The principle of conservation of energy implies that

> The directed sum of the electrical potential differences (voltage) around any closed network is zero, or:
>
> > More simply, the sum of the emfs in any closed loop is equivalent to the sum of the potential drops in that loop, or:
> >
> > > The algebraic sum of the products of the resistances of the conductors and the currents in them in a closed loop is equal to the total emf available in that loop.

Similarly to KCL, it can be stated as:

$$\sum_{k=1}^{n} V_k = 0$$

Here, n is the total number of voltages measured. The voltages may also be complex:

$$\sum_{k=1}^{n} \tilde{V}_k = 0$$

This law is based on the conservation of energy whereby voltage is defined as the energy per unit charge. The total amount of energy gained per unit charge must be equal to the amount of energy lost per unit charge, as energy and charge are both conserved.

Generalization

In the low-frequency limit, the voltage drop around any loop is zero. This includes imaginary loops arranged arbitrarily in space – not limited to the loops delineated by the circuit elements and conductors. In the low-frequency limit, this is a corollary of Faraday's law of induction (which is one of the Maxwell equations).

This has practical application in situations involving "static electricity".

3.1.3 Limitations

KCL and KVL both depend on the lumped element model being applicable to the circuit in question. When the model is not applicable, the laws do not apply.

KCL, in its usual form, is dependent on the assumption that current flows only in conductors, and that whenever current flows into one end of a conductor it immediately flows out the other end. This is not a safe assumption for high-frequency AC circuits, where the lumped element model is no longer applicable.[2] It is often possible to improve the applicability of KCL by considering "parasitic capacitances" distributed along the conductors.[2] Significant violations of KCL can occur[3] even at 60Hz, which is not a very high frequency.

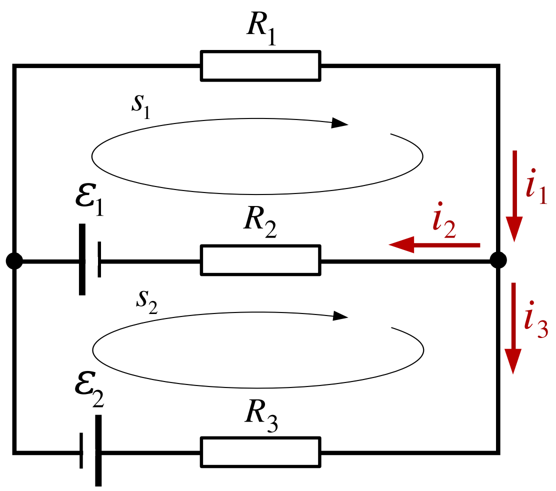
In other words, KCL is valid only if the total electric charge, Q , remains constant in the region being considered. In practical cases this is always so when KCL is applied at a geometric point. When investigating a finite region, however, it is possible that the charge density within the region may change. Since charge is conserved, this can only come about by a flow of charge across the region boundary. This flow represents a net current, and KCL is violated.

KVL is based on the assumption that there is no fluctuating magnetic field linking the closed loop. This is not a safe assumption for high-frequency (short-wavelength) AC circuits.[2] In the presence of a changing magnetic field the electric field is not a conservative vector field. Therefore the electric field cannot be the gradient of any potential. That is to say, the line integral of the electric field around the loop is not zero, directly contradicting KVL.

It is often possible to improve the applicability of KVL by considering "parasitic inductances" (including mutual inductances) distributed along the conductors.[2] These are treated as imaginary circuit elements that produce a voltage drop equal to the rate-of-change of the flux.

3.1.4 Example

Assume an electric network consisting of two voltage sources and three resistors.



According to the first law we have

$i_1 - i_2 - i_3 = 0$

The second law applied to the closed circuit s_1 gives

$-R_2 i_2 + \mathcal{E}_1 - R_1 i_1 = 0$

The second law applied to the closed circuit s_2 gives

$-R_3 i_3 - \mathcal{E}_2 - \mathcal{E}_1 + R_2 i_2 = 0$

Thus we get a linear system of equations in i_1, i_2, i_3 :

$$\begin{cases} i_1 - i_2 - i_3 & = 0 \\ -R_2 i_2 + \mathcal{E}_1 - R_1 i_1 & = 0 \\ -R_3 i_3 - \mathcal{E}_2 - \mathcal{E}_1 + R_2 i_2 & = 0 \end{cases}$$

Which is equivalent to

$$\begin{cases} i_1 + -i_2 + -i_3 & = 0 \\ R_1 i_1 + R_2 i_2 + 0 i_3 & = \mathcal{E}_1 \\ 0 i_1 + R_2 i_2 - R_3 i_3 & = \mathcal{E}_1 + \mathcal{E}_2 \end{cases}$$

Assuming

$R_1 = 100,\ R_2 = 200,\ R_3 = 300 \text{(ohms)}\ ;\ \mathcal{E}_1 = 3,\ \mathcal{E}_2 = 4 \text{(volts)}$

the solution is

$$\begin{cases} i_1 = \frac{1}{1100} \\ i_2 = \frac{4}{275} \\ i_3 = -\frac{3}{220} \end{cases}$$

i_3 has a negative sign, which means that the direction of i_3 is opposite to the assumed direction (the direction defined in the picture).

3.1.5 See also

- Faraday's law of induction
- Kirchhoff's laws (disambiguation)
- Lumped matter discipline

3.1.6 References

[1] Oldham, Kalil T. Swain (2008). *The doctrine of description: Gustav Kirchhoff, classical physics, and the "purpose of all science" in 19th-century Germany* (Ph. D.). University of California, Berkeley. p. 52. Docket 3331743.

[2] Ralph Morrison, *Grounding and Shielding Techniques in Instrumentation* Wiley-Interscience (1986) ISBN 0471838055

[3] simonjz05,. "High Voltage Cable Inspection" (video).

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3.2 Norton's theorem

This article is about the theorem in electrical circuits. For Norton's theorem for queueing networks, see flow-equivalent server method.

Known in Europe as the **Mayer–Norton theorem**, **Norton's theorem** holds, to illustrate in DC circuit theory terms, that (see image):

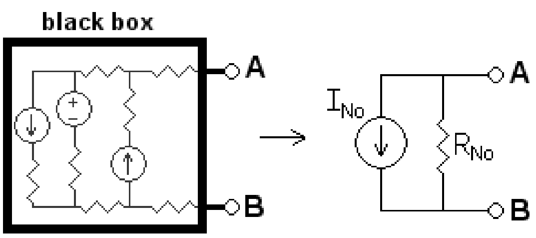
- Any linear electrical network with voltage and current sources and only resistances can be replaced at terminals A-B by an equivalent current source INO in parallel connection with an equivalent resistance RNO.

Edward Lawry Norton

- This equivalent current INO is the current obtained at terminals A-B of the network with terminals A-B short circuited.
- This equivalent resistance RNO is the resistance obtained at terminals A-B of the network with all its voltage sources short circuited and all its current sources open circuited.

For AC systems the theorem can be applied to reactive impedances as well as resistances.

The **Norton equivalent** circuit is used to represent any network of linear sources and impedances at a given frequency.



Any black box containing resistances only and voltage and current sources can be replaced by an equivalent circuit consisting of an equivalent current source in parallel connection with an equivalent resistance.

Norton's theorem and its dual, Thévenin's theorem, are widely used for circuit analysis simplification and to study circuit's initial-condition and steady-state response.

Norton's theorem was independently derived in 1926 by Siemens & Halske researcher Hans Ferdinand Mayer (1895–1980) and Bell Labs engineer Edward Lawry Norton (1898–1983).[1][2][3][4][5]

To find the equivalent,

1. Find the Norton current $I\mathrm{N_o}$. Calculate the output current, IAB, with a short circuit as the load (meaning 0 resistance between A and B). This is $\mathrm{IN_o}$.
2. Find the Norton resistance $R\mathrm{N_o}$. When there are no dependent sources (all current and voltage sources are independent), there are two methods of determining the Norton impedance $R\mathrm{N_o}$.

    - Calculate the output voltage, VAB, when in open circuit condition (i.e., no load resistor – meaning infinite load resistance). $R\mathrm{N_o}$ equals this VAB divided by $\mathrm{IN_o}$.

    or

    - Replace independent voltage sources with short circuits and independent current sources with open circuits. The total resistance across the output port is the Norton impedance $R\mathrm{N_o}$.

This is equivalent to calculating the Thevenin resistance.

However, when there are dependent sources, the more general method must be used. This method is not shown below in the diagrams.

- Connect a constant current source at the output terminals of the circuit with a value of 1 Ampere and calculate the voltage at its terminals. This voltage divided by the 1 A current is the Norton impedance $R\mathrm{N_o}$. This method must be used if the circuit contains dependent sources, but it can be used in all cases even when there are no dependent sources.

3.2.1 Example of a Norton equivalent circuit

In the example, the total current I_{total} is given by:

$$I_{\text{total}} = \frac{15\text{V}}{2\,\text{k}\Omega + (1\,\text{k}\Omega \| (1\,\text{k}\Omega + 1\,\text{k}\Omega))} = 5.625\text{mA}.$$

The current through the load is then, using the current divider rule:

$$I_{\text{No}} = \frac{1\,\text{k}\Omega + 1\,\text{k}\Omega}{(1\,\text{k}\Omega + 1\,\text{k}\Omega + 1\,\text{k}\Omega)} \cdot I_{\text{total}}$$

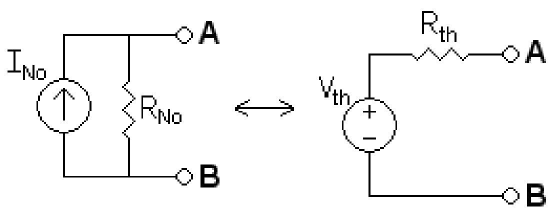
$= 2/3 \cdot 5.625\text{mA} = 3.75\text{mA}.$

And the equivalent resistance looking back into the circuit is:

$$R_{\text{eq}} = 1\,\text{k}\Omega + (2\,\text{k}\Omega \| (1\,\text{k}\Omega + 1\,\text{k}\Omega)) = 2\,\text{k}\Omega.$$

So the equivalent circuit is a 3.75 mA current source in parallel with a 2 kΩ resistor.

3.2.2 Conversion to a Thévenin equivalent



A Norton equivalent circuit is related to the Thévenin equivalent by the following equations:

$$R_{Th} = R_{No}$$

$$V_{Th} = I_{No} R_{No}$$

$$\frac{V_{Th}}{R_{Th}} = I_{No}$$

3.2.3 Queueing theory

The passive circuit equivalent of “Norton's theorem” in queuing theory is called the Chandy Herzog Woo theorem.[6][7] In a reversible queueing system, it is often possible to replace an uninteresting subset of queues by a single (FCFS or PS) queue with an appropriately chosen service rate.[8]

3.2.4 See also

- Ohm's Law
- Millman's theorem
- Source transformation
- Superposition theorem
- Thévenin's theorem
- Maximum power transfer theorem
- Extra element theorem

3.2.5 References

[1] Mayer

[2] Norton

[3] Johnson (2003b)

[4] Brittain

[5] Dorf

[6] Johnson (2003a)

[7] Gunther

[8] Chandy et al.

3.2.6 Bibliography

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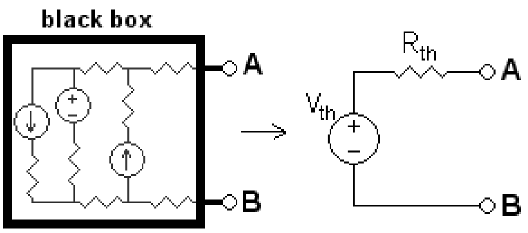
3.2.7 External links

- Norton's theorem at allaboutcircuits.com



Any black box containing resistances only and voltage and current sources can be replaced to a Thévenin equivalent circuit consisting of an equivalent voltage source in series connection with an equivalent resistance.

3.3 Thévenin's theorem

As originally stated in terms of DC resistive circuits only, **Thévenin's theorem** holds that:

- Any linear electrical network with voltage and current sources and only resistances can be replaced at terminals A-B by an equivalent voltage source V_{th} in series connection with an equivalent resistance R_{th}.
- This equivalent voltage V_{th} is the voltage obtained at terminals A-B of the network with terminals A-B open circuited.
- This equivalent resistance R_{th} is the resistance obtained at terminals A-B of the network with all its independent current sources open circuited and all its independent voltage sources short circuited.

In circuit theory terms, the theorem allows any one-port network to be reduced to a single voltage source and a single impedance.

The theorem also applies to frequency domain AC circuits consisting of reactive and resistive impedances.

The theorem was independently derived in 1853 by the German scientist Hermann von Helmholtz and in 1883 by Léon Charles Thévenin (1857–1926), an electrical engineer with France's national Postes et Télégraphes telecommunications organization.[1][2][3][4][5][6]

Thévenin's theorem and its dual, Norton's theorem, are widely used to make circuit analysis simpler and to study a circuit's initial-condition and steady-state response.[7][8] Thévenin's theorem can be used to convert any circuit's sources and impedances to a **Thévenin equivalent**; use of the theorem may in some cases be more convenient than use of Kirchhoff's circuit laws.[6][9]

3.3.1 Calculating the Thévenin equivalent

To calculate the equivalent circuit, the resistance and voltage are needed, so two equations are required. These two equations are usually obtained by using the following steps, but any conditions placed on the terminals of the circuit should also work:

1. Calculate the output voltage, VAB, when in open circuit condition (no load resistor—meaning infinite resistance). This is $V\mathrm{T_h}$.
2. Calculate the output current, IAB, when the output terminals are short circuited (load resistance is 0). $R\mathrm{T_h}$ equals $V\mathrm{T_h}$ divided by this IAB.

The equivalent circuit is a voltage source with voltage $V\mathrm{T_h}$ in series with a resistance $R\mathrm{T_h}$.

Step 2 could also be thought of as

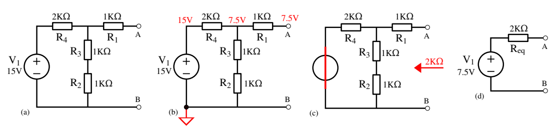
2a. Replace the independent voltage sources with short circuits, and independent current sources with open circuits.

2b. Calculate the resistance between terminals A and B. This is $R\mathrm{T_h}$.

The Thévenin-equivalent voltage is the voltage at the output terminals of the original circuit. When calculating a Thévenin-equivalent voltage, the voltage divider principle is often useful, by declaring one terminal to be V_{out} and the other terminal to be at the ground point.

The Thévenin-equivalent resistance is the resistance measured across points A and B "looking back" into the circuit. It is important to first replace all voltage- and current-sources with their internal resistances. For an ideal voltage source, this means replace the voltage source with a short circuit. For an ideal current source, this means replace the current source with an open circuit. Resistance can then be calculated across the terminals using the formulae for series and parallel circuits. This method is valid only for circuits with independent sources. If there are dependent sources in the circuit, another method must be used such as connecting a test source across A and B and calculating the voltage across or current through the test source.

Example



In the example, calculating the equivalent voltage:

$$V_{\mathrm{Th}} = \frac{R_2 + R_3}{(R_2 + R_3) + R_4} \cdot V_1$$

$$= \frac{1\,\mathrm{k}\Omega + 1\,\mathrm{k}\Omega}{(1\,\mathrm{k}\Omega + 1\,\mathrm{k}\Omega) + 2\,\mathrm{k}\Omega} \cdot 15\,\mathrm{V}$$

$$= \frac{1}{2} \cdot 15\,\mathrm{V} = 7.5\,\mathrm{V}$$

(notice that R_1 is not taken into consideration, as above calculations are done in an open circuit condition between A and B, therefore no current flows through this part, which means there is no current through R_1 and therefore no voltage drop along this part)

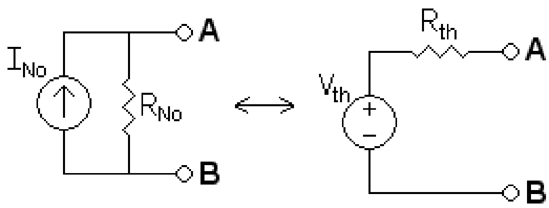
Calculating equivalent resistance:

$$R_{\mathrm{Th}} = R_1 + [(R_2 + R_3) \| R_4]$$
$$= 1\,\mathrm{k}\Omega + [(1\,\mathrm{k}\Omega + 1\,\mathrm{k}\Omega) \| 2\,\mathrm{k}\Omega]$$
$$= 1\,\mathrm{k}\Omega + \left(\frac{1}{(1\,\mathrm{k}\Omega + 1\,\mathrm{k}\Omega)} + \frac{1}{(2\,\mathrm{k}\Omega)}\right)^{-1} = 2\,\mathrm{k}\Omega.$$

3.3.2 Conversion to a Norton equivalent

Main article: Norton's theorem

A Norton equivalent circuit is related to the Thévenin



equivalent by the following:

$$R_{\mathrm{Th}} = R_{\mathrm{No}}$$
$$V_{\mathrm{Th}} = I_{\mathrm{No}} R_{\mathrm{No}}$$
$$I_{\mathrm{No}} = V_{\mathrm{Th}} / R_{\mathrm{Th}}.$$

3.3.3 Practical limitations

- Many circuits are only linear over a certain range of values, thus the Thévenin equivalent is valid only within this linear range.
- The Thévenin equivalent has an equivalent I–V characteristic only from the point of view of the load.
- The power dissipation of the Thévenin equivalent is not necessarily identical to the power dissipation of the real system. However, the power dissipated by an external resistor between the two output terminals is the same regardless of how the internal circuit is implemented.

3.3.4 A proof of the theorem

The proof involves two steps. First use superposition theorem to construct a solution, and then use uniqueness theorem to show the solution is unique. The second step is usually implied. Firstly, using the superposition theorem, in general for any linear "black box" circuit which contains voltage sources and resistors, one can always write down its voltage as a linear function of the corresponding current as follows

$$V = V_{\mathrm{Eq}} - Z_{\mathrm{Eq}} I$$

where the first term reflects the linear summation of contributions from each voltage source, while the second term measures the contribution from all the resistors. The above argument is due to the fact that the voltage of the black box for a given current I is identical to the linear superposition of the solutions of the following problems: (1) to leave the black box open circuited but activate individual voltage source one at a time and, (2) to short circuit all the voltage sources but feed the circuit with a certain ideal voltage source so that the resulting current exactly reads I (or an ideal current source of current I). Once the above expression is established, it is straightforward to show that V_{Eq} and Z_{Eq} are the single voltage source and the single series resistor in question.

3.3.5 See also

- Millman's theorem
- Source transformation
- Superposition theorem
- Norton's theorem
- Maximum power transfer theorem
- Extra element theorem

3.3.6 References

[1] Helmholtz

[2] Thévenin (1883a)

[3] Thévenin (1883b)

[4] Johnson (2003a)

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[6] Dorf

[7] Brenner

[8] Elgerd

[9] Dwight

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3.3.8 External links

- First-Order Filters: Shortcut via Thévenin Equivalent Source — showing on p. 4 complex circuit's Thévenin's theorem simplication to first-order low-pass filter and associated voltage divider, time constant and gain.

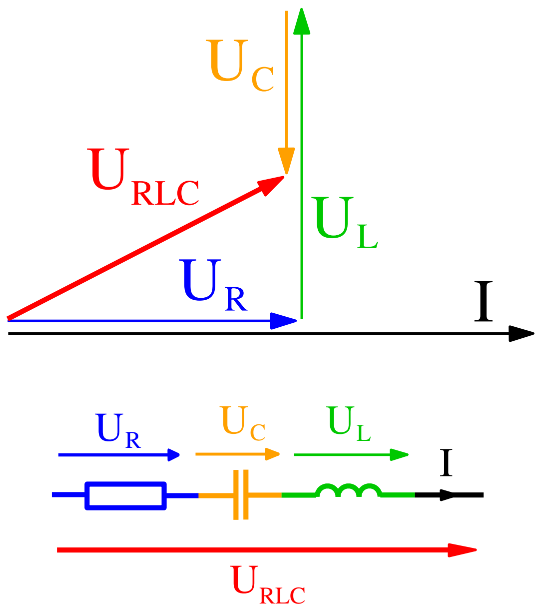
Chapter 4

AC analysis

4.1 Phasor

For other uses, see Phasor (disambiguation).
"Complex amplitude" redirects here. For the quantum-mechanical concept, see Complex probability amplitude.

In physics and engineering, a **phasor** (a portmanteau



An example of series RLC circuit and respective ***phasor diagram*** *for a specific* ω

of **phase vector**[1][2]), is a complex number representing a sinusoidal function whose amplitude (A), angular frequency (ω), and initial phase (θ) are time-invariant. It is related to a more general concept called analytic representation,[3] which decomposes a sinusoid into the product of a complex constant and a factor that encapsulates the frequency and time dependence. The complex constant, which encapsulates amplitude and phase dependence, is known as **phasor**, **complex amplitude**,[4][5] and (in older texts) **sinor**[6] or even **complexor**.[6]

A common situation in electrical networks is the existence of multiple sinusoids all with the same frequency, but different amplitudes and phases. The only difference in their analytic representations is the complex amplitude (phasor). A linear combination of such functions can be factored into the product of a linear combination of phasors (known as **phasor arithmetic**) and the time/frequency dependent factor that they all have in common.

The origin of the term phasor rightfully suggests that a (diagrammatic) calculus somewhat similar to that possible for vectors is possible for phasors as well.[6] An important additional feature of the phasor transform is that differentiation and integration of sinusoidal signals (having constant amplitude, period and phase) corresponds to simple algebraic operations on the phasors; the phasor transform thus allows the analysis (calculation) of the AC steady state of RLC circuits by solving simple algebraic equations (albeit with complex coefficients) in the phasor domain instead of solving differential equations (with real coefficients) in the time domain.[7][8] The originator of the phasor transform was Charles Proteus Steinmetz working at General Electric in the late 19th century.[9][10]

Glossing over some mathematical details, the phasor transform can also be seen as a particular case of the Laplace transform, which additionally can be used to (simultaneously) derive the transient response of an RLC circuit.[8][10] However, the Laplace transform is mathematically more difficult to apply and the effort may be unjustified if only steady state analysis is required.[10]

4.1.1 Definition

Euler's formula indicates that sinusoids can be represented mathematically as the sum of two complex-valued functions:

$$A \cdot \cos(\omega t + \theta) = A \cdot \frac{e^{i(\omega t+\theta)} + e^{-i(\omega t+\theta)}}{2},$$

[lower-alpha 1]

or as the real part of one of the functions:

$$A \cdot \cos(\omega t + \theta) = \operatorname{Re}\{A \cdot e^{i(\omega t+\theta)}\} = \operatorname{Re}\{A e^{i\theta} \cdot e^{i\omega t}\}.$$

The function $A \cdot e^{i(\omega t+\theta)}$ is the *analytic representation* of $A \cdot \cos(\omega t + \theta)$. Figure 2 depicts it as a rotating vector

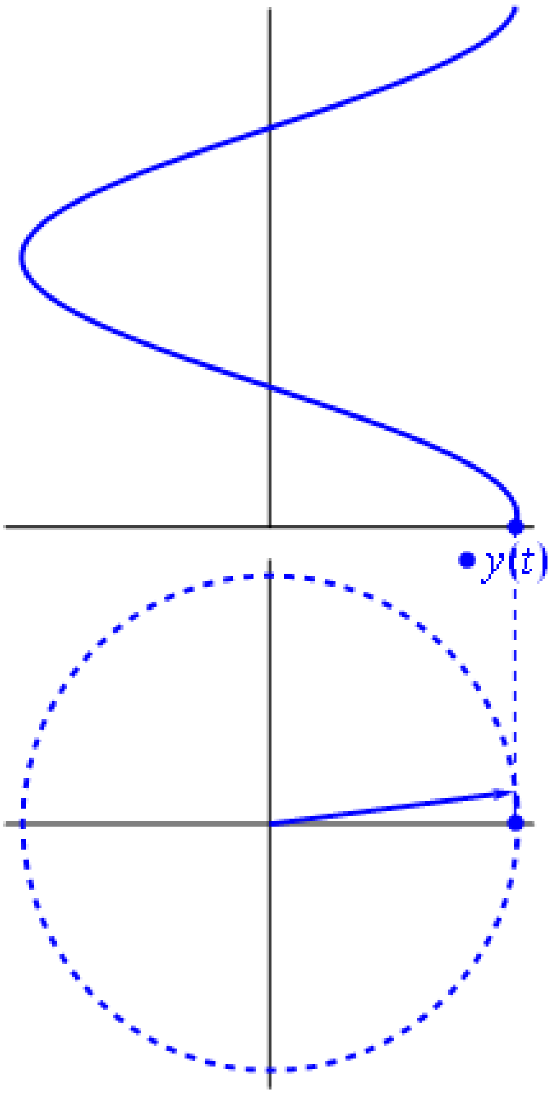


Fig 2. When function $A\cdot e^{i(\omega t+\theta)}$ is depicted in the complex plane, the vector formed by its imaginary and real parts rotates around the origin. Its magnitude is **A***, and it completes one cycle every 2π/ω seconds. θ is the angle it forms with the real axis at* t = *n•2π/ω, for integer values of n.*

in a complex plane. It is sometimes convenient to refer to the entire function as a *phasor*,[11] as we do in the next section. But the term usually implies just the static vector , $Ae^{i\theta}$. An even more compact representation is angle notation**:** $A\angle\theta$. See also vector notation.

4.1.2 Phasor arithmetic

Multiplication by a constant (scalar)

Multiplication of the phasor $Ae^{i\theta}e^{i\omega t}$ by a complex constant, $Be^{i\phi}$, produces another phasor. That means its only effect is to change the amplitude and phase of the underlying sinusoid**:**

$$\begin{aligned}\mathrm{Re}\{(Ae^{i\theta}\cdot Be^{i\phi})\cdot e^{i\omega t}\} &= \mathrm{Re}\{(ABe^{i(\theta+\phi)})\cdot e^{i\omega t}\}\\ &= AB\cos(\omega t+(\theta+\phi))\end{aligned}$$

In electronics, $Be^{i\phi}$ would represent an impedance, which is independent of time. In particular it is *not* the shorthand notation for another phasor. Multiplying a phasor current by an impedance produces a phasor voltage. But the product of two phasors (or squaring a phasor) would represent the product of two sinusoids, which is a non-linear operation that produces new frequency components. Phasor notation can only represent systems with one frequency, such as a linear system stimulated by a sinusoid.

Differentiation and integration

The time derivative or integral of a phasor produces another phasor.[lower-alpha 2] For example**:**

$$\mathrm{Re}\{\frac{d}{dt}(Ae^{i\theta}\cdot e^{i\omega t})\} = \mathrm{Re}\{Ae^{i\theta}\cdot i\omega e^{i\omega t}\} = \mathrm{Re}\{Ae^{i\theta}\cdot e^{i\pi/2}\omega e^{i\omega t}\} =$$

Therefore, in phasor representation, the time derivative of a sinusoid becomes just multiplication by the constant, $i\omega = (e^{i\pi/2}\cdot\omega)$.

Similarly, integrating a phasor corresponds to multiplication by $\frac{1}{i\omega} = \frac{e^{-i\pi/2}}{\omega}$. The time-dependent factor, $e^{i\omega t}$, is unaffected.

When we solve a linear differential equation with phasor arithmetic, we are merely factoring $e^{i\omega t}$ out of all terms of the equation, and reinserting it into the answer. For example, consider the following differential equation for the voltage across the capacitor in an RC circuit**:**

$$\frac{d\,v_C(t)}{dt} + \frac{1}{RC}v_C(t) = \frac{1}{RC}v_S(t)$$

When the voltage source in this circuit is sinusoidal**:**

$$v_S(t) = V_P\cdot\cos(\omega t+\theta),$$

we may substitute**:**

$$v_S(t) = \mathrm{Re}\{V_s\cdot e^{i\omega t}\}$$

$$v_C(t) = \mathrm{Re}\{V_c\cdot e^{i\omega t}\},$$

where phasor $V_s = V_P e^{i\theta}$, and phasor V_c is the unknown quantity to be determined.

In the phasor shorthand notation, the differential equation reduces to[lower-alpha 3]**:**

$$i\omega V_c + \frac{1}{RC}V_c = \frac{1}{RC}V_s$$

Solving for the phasor capacitor voltage gives:

$$V_c = \frac{1}{1+i\omega RC}\cdot(V_s) = \frac{1-i\omega RC}{1+(\omega RC)^2}\cdot(V_P e^{i\theta})$$

As we have seen, the factor multiplying V_s represents differences of the amplitude and phase of $v_C(t)$ relative to V_P and θ.

In polar coordinate form, it is:

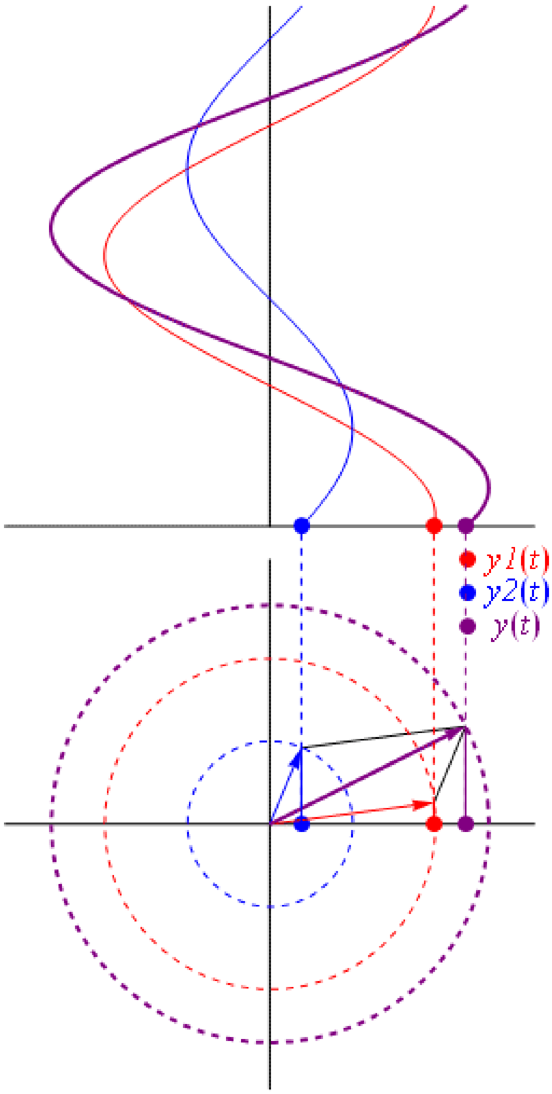
$$\frac{1}{\sqrt{1+(\omega RC)^2}}\cdot e^{-i\phi(\omega)},\ \text{where } \phi(\omega) = \arctan(\omega RC).$$

Therefore:

$$v_C(t) = \frac{1}{\sqrt{1+(\omega RC)^2}}\cdot V_P\cos(\omega t+\theta-\phi(\omega))$$

Addition

The sum of multiple phasors produces another phasor. That is because the sum of sinusoids with the same frequency is also a sinusoid with that frequency:



The sum of phasors as addition of rotating vectors

$$\begin{aligned}A_1\cos(\omega t+\theta_1)+A_2\cos(\omega t+\theta_2) &= \mathrm{Re}\{A_1e^{i\theta_1}e^{i\omega t}\}+\mathrm{Re}\{A_2e^{i\theta_2}e^{i\omega t}\}\\ &= \mathrm{Re}\{A_1e^{i\theta_1}e^{i\omega t}+A_2e^{i\theta_2}e^{i\omega t}\}\\ &= \mathrm{Re}\{(A_1e^{i\theta_1}+A_2e^{i\theta_2})e^{i\omega t}\}\\ &= \mathrm{Re}\{(A_3e^{i\theta_3})e^{i\omega t}\}\\ &= A_3\cos(\omega t+\theta_3),\end{aligned}$$

where:

$$A_3^2 = (A_1\cos\theta_1+A_2\cos\theta_2)^2+(A_1\sin\theta_1+A_2\sin\theta_2)^2,$$

$$\theta_3 = \arctan\left(\frac{A_1\sin\theta_1+A_2\sin\theta_2}{A_1\cos\theta_1+A_2\cos\theta_2}\right)$$

or, via the law of cosines on the complex plane (or the trigonometric identity for angle differences):

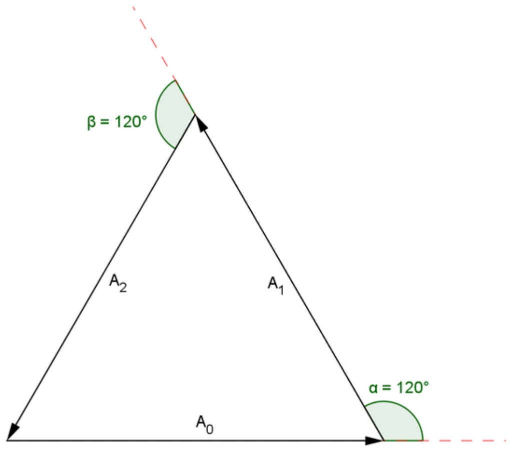
$$A_3^2 = A_1^2+A_2^2-2A_1A_2\cos(180^\circ-\Delta\theta), = A_1^2+A_2^2+2A_1A_2\cos(\Delta\theta),$$

where $\Delta\theta = \theta_1-\theta_2$. A key point is that A_3 and θ_3 do not depend on ω or t, which is what makes phasor notation possible. The time and frequency dependence can be suppressed and re-inserted into the outcome as long as the only operations used in between are ones that produce another phasor. In angle notation, the operation shown above is written:

$$A_1\angle\theta_1 + A_2\angle\theta_2 = A_3\angle\theta_3.$$

Another way to view addition is that two **vectors** with coordinates $[A_1\cos(\omega t+\theta_1), A_1\sin(\omega t+\theta_1)]$ and $[A_2\cos(\omega t+\theta_2), A_2\sin(\omega t+\theta_2)]$ are added vectorially to produce a resultant vector with coordinates $[A_3\cos(\omega t+\theta_3), A_3\sin(\omega t+\theta_3)]$. (see animation)

In physics, this sort of addition occurs when sinusoids interfere with each other, constructively or destructively. The static vector concept provides useful insight into questions like this: “What phase difference would be required between three identical sinusoids for perfect cancellation?" In this case, simply imagine taking three vectors of equal length and placing them head to tail such



Phasor diagram of three waves in perfect destructive interference

that the last head matches up with the first tail. Clearly, the shape which satisfies these conditions is an equilateral triangle, so the angle between each phasor to the next is 120° (2π/3 radians), or one third of a wavelength $^{\lambda}/_{3}$. So the phase difference between each wave must also be 120°, as is the case in three-phase power

In other words, what this shows is:

$$\cos(\omega t) + \cos(\omega t + 2\pi/3) + \cos(\omega t - 2\pi/3) = 0.$$

In the example of three waves, the phase difference between the first and the last wave was 240 degrees, while for two waves destructive interference happens at 180 degrees. In the limit of many waves, the phasors must form a circle for destructive interference, so that the first phasor is nearly parallel with the last. This means that for many sources, destructive interference happens when the first and last wave differ by 360 degrees, a full wavelength λ . This is why in single slit diffraction, the minima occurs when light from the far edge travels a full wavelength further than the light from the near edge.

4.1.3 Phasor diagrams

Electrical engineers, electronics engineers, electronic engineering technicians and aircraft engineers all use phasor diagrams to visualize complex constants and variables (phasors). Like vectors, arrows drawn on graph paper or computer displays represent phasors. Cartesian and polar representations each have advantages, with the Cartesian coordinates showing the real and imaginary parts of the phasor and the polar coordinates showing its magnitude and phase.

4.1.4 Applications

Circuit laws

With phasors, the techniques for solving DC circuits can be applied to solve AC circuits. A list of the basic laws is given below.

- **Ohm's law for resistors:** a resistor has no time delays and therefore doesn't change the phase of a signal therefore *V=IR* remains valid.

- **Ohm's law for resistors, inductors, and capacitors:** $V = IZ$ where Z is the complex impedance.

- In an AC circuit we have real power (P) which is a representation of the average power into the circuit and reactive power (Q) which indicates power flowing back and forward. We can also define the complex power $S = P + jQ$ and the apparent power which is the magnitude of S. The power law for an AC circuit expressed in phasors is then $S = VI^*$ (where I^* is the complex conjugate of I, and I and V are the RMS values of the voltage and current).

- Kirchhoff's circuit laws work with phasors in complex form

Given this we can apply the techniques of analysis of resistive circuits with phasors to analyze single frequency AC circuits containing resistors, capacitors, and inductors. Multiple frequency linear AC circuits and AC circuits with different waveforms can be analyzed to find voltages and currents by transforming all waveforms to sine wave components with magnitude and phase then analyzing each frequency separately, as allowed by the superposition theorem.

Power engineering

In analysis of three phase AC power systems, usually a set of phasors is defined as the three complex cube roots of unity, graphically represented as unit magnitudes at angles of 0, 120 and 240 degrees. By treating polyphase AC circuit quantities as phasors, balanced circuits can be simplified and unbalanced circuits can be treated as an algebraic combination of symmetrical circuits. This approach greatly simplifies the work required in electrical calculations of voltage drop, power flow, and short-circuit currents. In the context of power systems analysis, the phase angle is often given in degrees, and the magnitude in rms value rather than the peak amplitude of the sinusoid.

The technique of synchrophasors uses digital instruments to measure the phasors representing transmission system voltages at widespread points in a transmission network. Small changes in the phasors are sensitive indicators of power flow and system stability.

4.1.5 See also

- In-phase and quadrature components
- Analytic signal
  - Complex envelope
- Phase factor, a phasor of unit magnitude

4.1.6 Footnotes

[1]
- **i** is the Imaginary unit ($i^2 = -1$).
- In electrical engineering texts, the imaginary unit is often symbolized by j.
- The frequency of the wave, in Hz, is given by $\omega/2\pi$.

[2] This results from: $\frac{d}{dt}(e^{i\omega t}) = i\omega e^{i\omega t}$ which means that the complex exponential is the eigenfunction of the derivative operation.

[3] **Proof:**

Since this must hold for all t , specifically: $t - \frac{\pi}{2\omega}$, it follows that:

It is also readily seen that:

$$\frac{d\ \mathrm{Re}\{V_c \cdot e^{i\omega t}\}}{dt} = \mathrm{Re}\left\{\frac{d\left(V_c \cdot e^{i\omega t}\right)}{dt}\right\} = \mathrm{Re}\left\{i\omega V_c \cdot e^{i\omega t}\right\}$$

$$\frac{d\ \mathrm{Im}\{V_c \cdot e^{i\omega t}\}}{dt} = \mathrm{Im}\left\{\frac{d\left(V_c \cdot e^{i\omega t}\right)}{dt}\right\} = \mathrm{Im}\left\{i\omega V_c \cdot e^{i\omega t}\right\}$$

Substituting these into **Eq.1** and **Eq.2**, multiplying **Eq.2** by $i,$ and adding both equations gives:

$$i\omega V_c \cdot e^{i\omega t} + \frac{1}{RC}V_c \cdot e^{i\omega t} = \frac{1}{RC}V_s \cdot e^{i\omega t}$$

$$\left(i\omega V_c + \frac{1}{RC}V_c\right) \cdot e^{i\omega t} = \left(\frac{1}{RC}V_s\right) \cdot e^{i\omega t}$$

$$i\omega V_c + \frac{1}{RC}V_c = \frac{1}{RC}V_s \qquad \text{(QED)}$$

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4.1.8 Further reading

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- Dorf, Richard C.; Tallarida, Ronald J. (1993-07-15). *Pocket Book of Electrical Engineering Formulas* (1 ed.). Boca Raton,FL: CRC Press. pp. 152–155. ISBN 0849344735.

4.1.9 External links

- Phasor Phactory
- Visual Representation of Phasors
- Polar and Rectangular Notation

4.2 Electric power

Electric power is the rate at which electrical energy is transferred by an electric circuit. The SI unit of power is the watt, one joule per second.

Electric power is usually produced by electric generators, but can also be supplied by sources such as electric batteries. It is generally supplied to businesses and homes by the electric power industry through an electric power grid. Electric power is usually sold by the kilowatt hour

Electric power is transmitted on overhead lines like these, and also on underground high voltage cables.

(3.6 MJ) which is the product of power in kilowatts multiplied by running time in hours. Electric utilities measure power using an electricity meter, which keeps a running total of the electric energy delivered to a customer.

Electrical power provides a low entropy form of energy and can be converted into motion or other forms of energy with high efficiency.[1]

4.2.1 Definition

Electric power, like mechanical power, is the rate of doing work, measured in watts, and represented by the letter *P*. The term *wattage* is used colloquially to mean "electric power in watts." The electric power in watts produced by an electric current *I* consisting of a charge of *Q* coulombs every *t* seconds passing through an electric potential (voltage) difference of *V* is

$$P = \text{time unit per done work} = \frac{VQ}{t} = VI$$

where

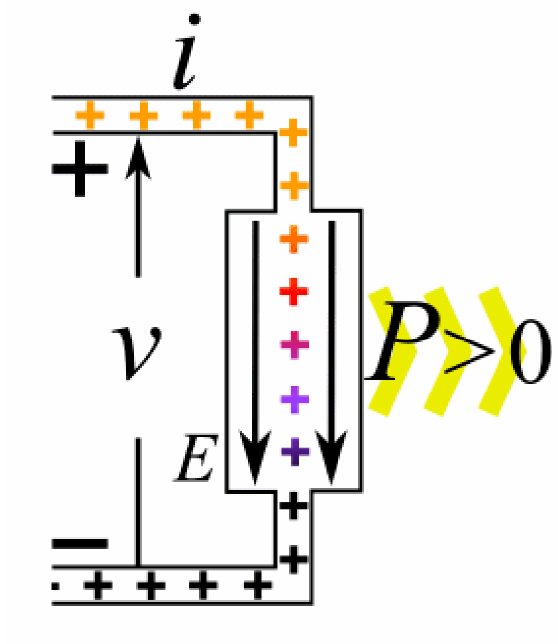
Q is electric charge in coulombs

t is time in seconds

I is electric current in amperes

V is electric potential or voltage in volts

4.2.2 Explanation

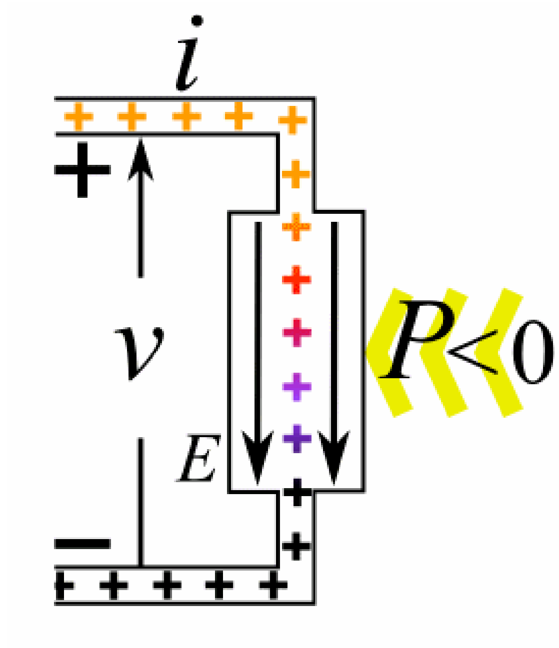


Animation showing electric load

Electric power is transformed to other forms of energy when electric charges move through an electric potential (voltage) difference, which occurs in electrical components in electric circuits. From the standpoint of electric power, components in an electric circuit can be divided into two categories:

- **Passive devices** or **loads**: When electric charges move through a potential difference from a higher to a lower voltage, that is when conventional current (positive charge) moves from the positive (+) terminal to the negative (−) terminal, work is done by the charges on the device. The potential energy of the charges due to the voltage between the terminals is converted to kinetic energy in the device. These devices are called *passive* components or *loads*; they 'consume' electric power from the circuit, converting it to other forms of energy such as mechanical work, heat, light, etc. Examples are electrical appliances, such as light bulbs, electric motors, and electric heaters. In alternating current (AC) circuits the direction of the voltage periodically reverses, but the current always flows from the higher potential to the lower potential side.

- **Active devices** or **power sources**: If the charges are moved by an 'exterior force' through the device



Animation showing power source

in the direction from the lower electric potential to the higher, (so positive charge moves from the negative to the positive terminal), work will be done *on* the charges, and energy is being converted to electric potential energy from some other type of energy, such as mechanical energy or chemical energy. Devices in which this occurs are called *active* devices or *power sources*; such as electric generators and batteries.

Some devices can be either a source or a load, depending on the voltage and current through them. For example, a rechargeable battery acts as a source when it provides power to a circuit, but as a load when it is connected to a battery charger and is being recharged.

Passive sign convention

Main article: Passive sign convention

Since electric power can flow either into or out of a component, a convention is needed for which direction represents positive power flow. Electric power flowing *out* of a circuit *into* a component is arbitrarily defined to have a positive sign, while power flowing *into* a circuit from a component is defined to have a negative sign. Thus passive components have positive power consumption, while power sources have negative power consumption. This is called the *passive sign convention*.

Resistive circuits

In the case of resistive (Ohmic, or linear) loads, Joule's law can be combined with Ohm's law ($V = I{\cdot}R$) to produce alternative expressions for the amount of power that is dissipated:

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

where R is the electrical resistance.

Alternating current

Main article: AC power

In alternating current circuits, energy storage elements such as inductance and capacitance may result in periodic reversals of the direction of energy flow. The portion of power flow that, averaged over a complete cycle of the AC waveform, results in net transfer of energy in one direction is known as real power (also referred to as active power). That portion of power flow due to stored energy, that returns to the source in each cycle, is known as reactive power. The real power $\boldsymbol{P}$ in watts consumed by a device is given by

$$P = \frac{1}{2} V_p I_p \cos\theta = V_{rms} I_{rms} \cos\theta$$

where

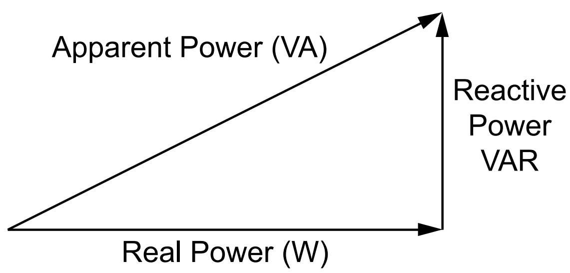
$\boldsymbol{V}_{\mathrm{p}}$ is the peak voltage in volts

$\boldsymbol{I}_{\mathrm{p}}$ is the peak current in amperes

$\boldsymbol{V}_{\mathrm{rms}}$ is the root-mean-square voltage in volts

$\boldsymbol{I}_{\mathrm{rms}}$ is the root-mean-square current in amperes

$\boldsymbol{\theta}$ is the phase angle between the current and voltage sine waves



Power triangle: The components of AC power

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

$$(\text{apparent power})^2 = (\text{real power})^2 + (\text{reactive power})^2$$

Real and reactive powers can also be calculated directly from the apparent power, when the current and voltage are both sinusoids with a known phase angle θ between them:

$$(\text{real power}) = (\text{apparent power}) \cos\theta$$

$$(\text{reactive power}) = (\text{apparent power}) \sin\theta$$

The ratio of real power to apparent power is called power factor and is a number always between 0 and 1. Where the currents and voltages have non-sinusoidal forms, power factor is generalized to include the effects of distortion

Electromagnetic fields

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

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

The result is a scalar since it is the *surface integral* of the *Poynting vector*.

4.2.3 Electric power generation

Main article: electricity generation

The fundamental principles of much electricity generation were discovered during the 1820s and early 1830s by the British scientist Michael Faraday. His basic method is still used today: electricity is generated by the movement of a loop of wire, or disc of copper between the poles of a magnet.

For electric utilities, it is the first process in the delivery of electricity to consumers. The other processes, electricity transmission, distribution, and electrical power storage and recovery using pumped-storage methods are normally carried out by the electric power industry.

Electricity is mostly generated at a power station by electromechanical generators, driven by heat engines heated by combustion, geothermal power or nuclear fission. Other generators are driven by the kinetic energy of flowing water and wind. There are many other technologies that are used to generate electricity such as solar photovoltaics.

A battery is a device consisting of one or more electrochemical cells that convert stored chemical energy into electrical energy.[2] Since the invention of the first battery (or "voltaic pile") in 1800 by Alessandro Volta and especially since the technically improved Daniell cell in 1836, batteries have become a common power source for many household and industrial applications. According to a 2005 estimate, the worldwide battery industry generates US$48 billion in sales each year,[3] with 6% annual growth. There are two types of batteries: primary batteries (disposable batteries), which are designed to be used once and discarded, and secondary batteries (rechargeable batteries), which are designed to be recharged and used multiple times. Batteries come in many sizes, from miniature cells used to power hearing aids and wristwatches to battery banks the size of rooms that provide standby power for telephone exchanges and computer data centers.

4.2.4 Electric power industry

Main article: electric power industry

The electric power industry provides the production and delivery of power, in sufficient quantities to areas that need electricity, through a grid connection. The grid distributes electrical energy to customers. Electric power is generated by central power stations or by distributed generation.

Many households and businesses need access to electricity, especially in developed nations, the demand being scarcer in developing nations. Demand for electricity is derived from the requirement for electricity in order to operate domestic appliances, office equipment, industrial machinery and provide sufficient energy for both domestic and commercial lighting, heating, cooking and industrial processes. Because of this aspect the industry is viewed as part of the public utility infrastructure.

4.2.5 See also

- Electric power system
- Power engineering
- EGRID
- Electric energy consumption
- High voltage cable

- Rural electrification

4.2.6 Notes

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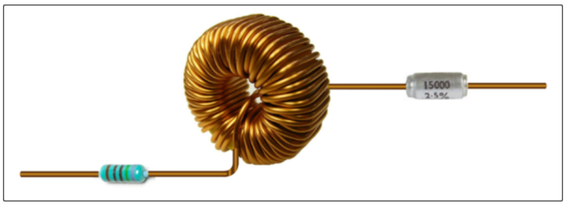
4.2.8 External links

- U.S. Department of Energy: Electric Power
- GlobTek, Inc. Glossary of Electric power Power Supply Terms

4.3 RLC circuit



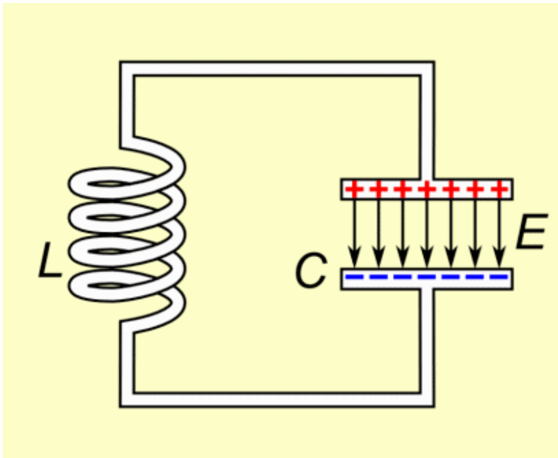
A series RLC circuit: a resistor, inductor, and a capacitor

An **RLC circuit** is an electrical circuit consisting of a resistor (R), an inductor (L), and a capacitor (C), connected in series or in parallel. The name of the circuit is derived from the letters that are used to denote the constituent components of this circuit, where the sequence of the components may vary from RLC.

The circuit forms a harmonic oscillator for current, and resonates in a similar way as an LC circuit. Introducing the resistor increases the decay of these oscillations, which is also known as damping. The resistor also reduces the peak resonant frequency. Some resistance is unavoidable in real circuits even if a resistor is not specifically included as a component. An ideal, pure LC circuit is an abstraction used in theoretical considerations.

RLC circuits have many applications as oscillator circuits. Radio receivers and television sets use them for tuning to select a narrow frequency range from ambient radio waves. In this role the circuit is often referred to as a tuned circuit. An RLC circuit can be used as a band-pass filter, band-stop filter, low-pass filter or high-pass filter. The tuning application, for instance, is an example of band-pass filtering. The RLC filter is described as a *second-order* circuit, meaning that any voltage or current in the circuit can be described by a second-order differential equation in circuit analysis.

The three circuit elements, R,L and C can be combined in a number of different topologies. All three elements in series or all three elements in parallel are the simplest in concept and the most straightforward to analyse. There are, however, other arrangements, some with practical importance in real circuits. One issue often encountered is the need to take into account inductor resistance. Inductors are typically constructed from coils of wire, the resistance of which is not usually desirable, but it often has a significant effect on the circuit.



Animation illustrating the operation of an LC circuit, an RLC circuit with no resistance. Charge flows back and forth between the capacitor plates through the inductance. The energy oscillates back and forth between the capacitor's electric field (E) *and the inductor's magnetic field* (B) *RLC circuits operate similarly, except that the oscillating currents decay with time to zero due to the resistance in the circuit.*

4.3.1 Basic concepts

Resonance

An important property of this circuit is its ability to resonate at a specific frequency, the resonance frequency, f_0 . Frequencies are measured in units of hertz. In this article, however, angular frequency, ω_0 , is used which is more mathematically convenient. This is measured in radians per second. They are related to each other by a simple proportion,

$$\omega_0 = 2\pi f_0$$

Resonance occurs because energy is stored in two different ways: in an electric field as the capacitor is charged and in a magnetic field as current flows through the inductor. Energy can be transferred from one to the other within the circuit and this can be oscillatory. A mechanical analogy is a weight suspended on a spring which will oscillate up and down when released. This is no passing metaphor; a weight on a spring is described by exactly the same second order differential equation as an RLC circuit and for all the properties of the one system there will be found an analogous property of the other. The mechanical property answering to the resistor in the circuit is friction in the spring/weight system. Friction will slowly bring any oscillation to a halt if there is no external force driving it. Likewise, the resistance in an RLC circuit will “damp” the oscillation, diminishing it with time if there is no driving AC power source in the circuit.

The resonance frequency is defined as the frequency at which the impedance of the circuit is at a minimum. Equivalently, it can be defined as the frequency at which the impedance is purely real (that is, purely resistive). This occurs because the impedances of the inductor and capacitor at resonance are equal but of opposite sign and cancel out. Circuits where L and C are in parallel rather than series actually have a maximum impedance rather than a minimum impedance. For this reason they are often described as antiresonators, it is still usual, however, to name the frequency at which this occurs as the resonance frequency.

Natural frequency

The resonance frequency is defined in terms of the impedance presented to a driving source. It is still possible for the circuit to carry on oscillating (for a time) after the driving source has been removed or it is subjected to a step in voltage (including a step down to zero). This is similar to the way that a tuning fork will carry on ringing after it has been struck, and the effect is often called ringing. This effect is the peak natural resonance frequency of the circuit and in general is not exactly the same as the driven resonance frequency, although the two will usually be quite close to each other. Various terms are used by different authors to distinguish the two, but resonance frequency unqualified usually means the driven resonance frequency. The driven frequency may be called the undamped resonance frequency or undamped natural frequency and the peak frequency may be called the damped resonance frequency or the damped natural frequency. The reason for this terminology is that the driven resonance frequency in a series or parallel resonant circuit has the value[1]

$$\omega_0 = \frac{1}{\sqrt{LC}}$$

This is exactly the same as the resonance frequency of an LC circuit, that is, one with no resistor present. The resonant frequency for an RLC circuit is the same as a circuit in which there is no damping, hence undamped resonance frequency. The peak resonance frequency, on the other hand, depends on the value of the resistor and is described as the damped resonant frequency. A highly damped circuit will fail to resonate at all when not driven. A circuit with a value of resistor that causes it to be just on the edge of ringing is called critically damped. Either side of critically damped are described as underdamped (ringing happens) and overdamped (ringing is suppressed).

Circuits with topologies more complex than straightforward series or parallel (some examples described later in the article) have a driven resonance frequency that deviates from $\omega_0 = \frac{1}{\sqrt{LC}}$ and for those the undamped resonance frequency, damped resonance frequency and driven resonance frequency can all be different.

Damping

Damping is caused by the resistance in the circuit. It determines whether or not the circuit will resonate naturally (that is, without a driving source). Circuits which will resonate in this way are described as underdamped and those that will not are overdamped. Damping attenuation (symbol α) is measured in nepers per second. However, the unitless damping factor (symbol ζ, zeta) is often a more useful measure, which is related to α by

$$\zeta = \frac{\alpha}{\omega_0}$$

The special case of $\zeta = 1$ is called critical damping and represents the case of a circuit that is just on the border of oscillation. It is the minimum damping that can be applied without causing oscillation.

Bandwidth

The resonance effect can be used for filtering, the rapid change in impedance near resonance can be used to pass or block signals close to the resonance frequency. Both band-pass and band-stop filters can be constructed and some filter circuits are shown later in the article. A key parameter in filter design is bandwidth. The bandwidth is measured between the 3dB-points, that is, the frequencies at which the power passed through the circuit has fallen to half the value passed at resonance. There are two of these half-power frequencies, one above, and one below the resonance frequency

$$\Delta\omega = \omega_2 - \omega_1$$

where $\Delta\omega$ is the bandwidth, ω_1 is the lower half-power frequency and ω_2 is the upper half-power frequency. The bandwidth is related to attenuation by,

$$\Delta\omega = 2\alpha$$

when the units are radians per second and nepers per second respectively. Other units may require a conversion factor. A more general measure of bandwidth is the fractional bandwidth, which expresses the bandwidth as a fraction of the resonance frequency and is given by

$$F_\mathrm{b} = \frac{\Delta\omega}{\omega_0}$$

The fractional bandwidth is also often stated as a percentage. The damping of filter circuits is adjusted to result in the required bandwidth. A narrow band filter, such as a notch filter, requires low damping. A wide band filter requires high damping.

Q factor

The Q factor is a widespread measure used to characterise resonators. It is defined as the peak energy stored in the circuit divided by the average energy dissipated in it per radian at resonance. Low Q circuits are therefore damped and lossy and high Q circuits are underdamped. Q is related to bandwidth; low Q circuits are wide band and high Q circuits are narrow band. In fact, it happens that Q is the inverse of fractional bandwidth

$$Q = \frac{1}{F_\mathrm{b}} = \frac{\omega_0}{\Delta\omega}$$

Q factor is directly proportional to selectivity, as Q factor depends inversely on bandwidth.

For a series resonant circuit, the Q factor can be calculated as follows:[2]

$$Q = \frac{1}{\omega_0 RC} = \frac{\omega_0 L}{R} = \frac{1}{R}\sqrt{\frac{L}{C}}$$

Scaled parameters

The parameters ζ, F_b, and Q are all scaled to ω_0. This means that circuits which have similar parameters share similar characteristics regardless of whether or not they are operating in the same frequency band.

The article next gives the analysis for the series RLC circuit in detail. Other configurations are not described in such detail, but the key differences from the series case are given. The general form of the differential equations given in the series circuit section are applicable to all second order circuits and can be used to describe the voltage or current in any element of each circuit.

4.3.2 Series RLC circuit

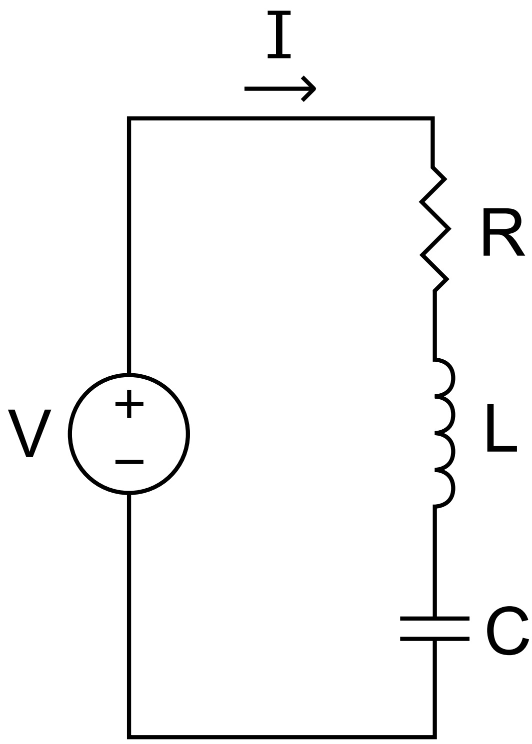


Figure 1: *RLC series circuit*

- V, *the voltage source powering the circuit*
- I, *the current admitted through the circuit*
- R, *the effective resistance of the combined load, source, and components*
- L, *the inductance of the inductor component*
- C, *the capacitance of the capacitor component*

In this circuit, the three components are all in series with the voltage source. The governing differential equation can be found by substituting into Kirchhoff's voltage law (KVL) the constitutive equation for each of the three elements. From KVL,

$$v_R + v_L + v_C = v(t)$$

where v_R, v_L, v_C are the voltages across R, L and C respectively and $v(t)$ is the time varying voltage from the source. Substituting in the constitutive equations,

$$Ri(t) + L\frac{di}{dt} + \frac{1}{C}\int_{-\infty}^{\tau=t} i(\tau)\,d\tau = v(t)$$

For the case where the source is an unchanging voltage, differentiating and dividing by L leads to the second order differential equation:

$$\frac{d^2i(t)}{dt^2} + \frac{R}{L}\frac{di(t)}{dt} + \frac{1}{LC}i(t) = 0$$

This can usefully be expressed in a more generally applicable form:

$$\frac{d^2i(t)}{dt^2} + 2\alpha\frac{di(t)}{dt} + {\omega_0}^2 i(t) = 0$$

α and ω_0 are both in units of angular frequency. α is called the *neper frequency*, or *attenuation*, and is a measure of how fast the transient response of the circuit will die away after the stimulus has been removed. Neper occurs in the name because the units can also be considered to be nepers per second, neper being a unit of attenuation. ω_0 is the angular resonance frequency.[3]

For the case of the series RLC circuit these two parameters are given by:[4]

$$\alpha = \frac{R}{2L}$$
$$\omega_0 = \frac{1}{\sqrt{LC}}$$

A useful parameter is the *damping factor*, ζ, which is defined as the ratio of these two; although, sometimes α is referred to as the damping factor and ζ is not used.[5]

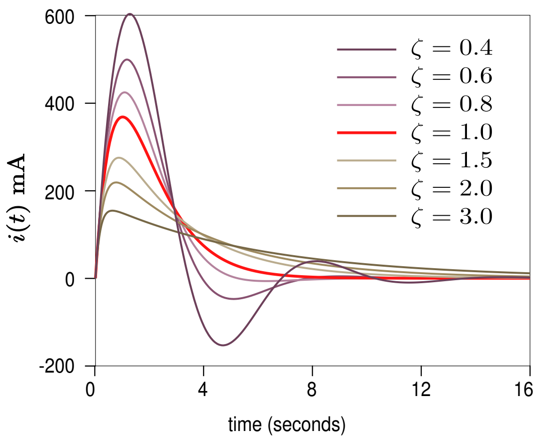
$$\zeta = \frac{\alpha}{\omega_0}$$

In the case of the series RLC circuit, the damping factor is given by,

$$\zeta = \frac{R}{2}\sqrt{\frac{C}{L}}$$

The value of the damping factor determines the type of transient that the circuit will exhibit.[6]

Transient response



Plot showing underdamped and overdamped responses of a series RLC circuit. The critical damping plot is the bold red curve. The plots are normalised for L = *1,* C = *1 and* $\omega_0 = 1$

The differential equation for the circuit solves in three different ways depending on the value of ζ. These are underdamped ($\zeta < 1$), overdamped ($\zeta > 1$) and critically damped ($\zeta = 1$). The differential equation has the characteristic equation,[7]

$$s^2 + 2\alpha s + {\omega_0}^2 = 0$$

The roots of the equation in *s* are,[7]

$$s_1 = -\alpha + \sqrt{\alpha^2 - {\omega_0}^2}$$
$$s_2 = -\alpha - \sqrt{\alpha^2 - {\omega_0}^2}$$

The general solution of the differential equation is an exponential in either root or a linear superposition of both,

$$i(t) = A_1 e^{s_1 t} + A_2 e^{s_2 t}$$

The coefficients A_1 and A_2 are determined by the boundary conditions of the specific problem being analysed. That is, they are set by the values of the currents and voltages in the circuit at the onset of the transient and the presumed value they will settle to after infinite time.[8]

Overdamped response The overdamped response ($\zeta > 1$) is,[9]

$$i(t) = A_1 e^{-\omega_0\left(\zeta + \sqrt{\zeta^2-1}\right)t} + A_2 e^{-\omega_0\left(\zeta - \sqrt{\zeta^2-1}\right)t}$$

The overdamped response is a decay of the transient current without oscillation.[10]

Underdamped response The underdamped response ($\zeta < 1$) is,[11]

$$i(t) = B_1 e^{-\alpha t} \cos(\omega_d t) + B_2 e^{-\alpha t} \sin(\omega_d t)$$

By applying standard trigonometric identities the two trigonometric functions may be expressed as a single sinusoid with phase shift,[12]

$$i(t) = B_3 e^{-\alpha t} \sin(\omega_d t + \varphi)$$

The underdamped response is a decaying oscillation at frequency ω_d . The oscillation decays at a rate determined by the attenuation α . The exponential in α describes the envelope of the oscillation. B_1 and B_2 (or B_3 and the phase shift φ in the second form) are arbitrary constants determined by boundary conditions. The frequency ω_d is given by,[11]

$$\omega_d = \sqrt{{\omega_0}^2 - \alpha^2} = \omega_0 \sqrt{1 - \zeta^2}$$

This is called the damped resonance frequency or the damped natural frequency. It is the frequency the circuit will naturally oscillate at if not driven by an external source. The resonance frequency, ω_0 , which is the frequency at which the circuit will resonate when driven by an external oscillation, may often be referred to as the undamped resonance frequency to distinguish it.[13]

Critically damped response The critically damped response ($\zeta = 1$) is,[14]

$$i(t) = D_1 t e^{-\alpha t} + D_2 e^{-\alpha t}$$

The critically damped response represents the circuit response that decays in the fastest possible time without going into oscillation. This consideration is important in control systems where it is required to reach the desired state as quickly as possible without overshooting. D_1 and D_2 are arbitrary constants determined by boundary conditions.[15]

Laplace domain

The series RLC can be analyzed for both transient and steady AC state behavior using the Laplace transform.[16] If the voltage source above produces a waveform with Laplace-transformed $V(s)$ (where s is the complex frequency $s = \sigma + i\omega$), KVL can be applied in the Laplace domain:

$$V(s) = I(s) \left(R + Ls + \frac{1}{Cs} \right)$$

where $I(s)$ is the Laplace-transformed current through all components. Solving for $I(s)$:

$$I(s) = \frac{1}{R + Ls + \frac{1}{Cs}} V(s)$$

And rearranging, we have that

$$I(s) = \frac{s}{L\left(s^2 + \frac{R}{L}s + \frac{1}{LC}\right)} V(s)$$

Laplace admittance Solving for the Laplace admittance $Y(s)$:

$$Y(s) = \frac{I(s)}{V(s)} = \frac{s}{L\left(s^2 + \frac{R}{L}s + \frac{1}{LC}\right)}$$

Simplifying using parameters α and ω_o defined in the previous section, we have

$$Y(s) = \frac{I(s)}{V(s)} = \frac{s}{L\left(s^2 + 2\alpha s + {\omega_0}^2\right)}$$

Poles and zeros The zeros of $Y(s)$ are those values of s such that $Y(s) = 0$:

$$s = 0 \text{ and } |s| \to \infty$$

The poles of $Y(s)$ are those values of s such that $Y(s) \to \infty$. By the quadratic formula, we find

$$s = -\alpha \pm \sqrt{\alpha^2 - {\omega_0}^2}$$

The poles of $Y(s)$ are identical to the roots s_1 and s_2 of the characteristic polynomial of the differential equation in the section above.

General solution For an arbitrary $E(t)$, the solution obtained by inverse transform of $I(s)$ is:

- In the underdamped case, $\omega_0 > \alpha$:

$$I(t) = \frac{1}{L}\int_0^t E(t-\tau)e^{-\alpha\tau}\left(\cos\omega_d\tau - \frac{\alpha}{\omega_d}\sin\omega_d\tau\right)\,d\tau$$

- In the critically damped case, $\omega_0 = \alpha$

$$I(t) = \frac{1}{L}\int_0^t E(t-\tau)e^{-\alpha\tau}(1-\alpha\tau)\,d\tau$$

- In the overdamped case, $\omega_0 < \alpha$:

$$I(t) = \frac{1}{L}\int_0^t E(t-\tau)e^{-\alpha\tau}\left(\cosh\omega_r\tau - \frac{\alpha}{\omega_r}\sinh\omega_r\tau\right)\,d\tau$$

where $\omega_r = \sqrt{\alpha^2 - \omega_0^2}$, and cosh and sinh are the usual hyperbolic functions.

Sinusoidal steady state Sinusoidal steady state is represented by letting $s = j\omega$, where j is the imaginary unit.

Taking the magnitude of the above equation with this substitution:

$$|Y(s = j\omega)| = \frac{1}{\sqrt{R^2 + \left(\omega L - \frac{1}{\omega C}\right)^2}}.$$

and the current as a function of ω can be found from

$$|I(j\omega)| = |Y(j\omega)||V(j\omega)|.$$

There is a peak value of $|I(j\omega)|$. The value of ω at this peak is, in this particular case, equal to the undamped natural resonance frequency:[17]

$$\omega_0 = \frac{1}{\sqrt{LC}}.$$

4.3.3 Parallel RLC circuit

The properties of the parallel RLC circuit can be obtained from the duality relationship of electrical circuits and considering that the parallel RLC is the dual impedance of a series RLC. Considering this, it becomes clear that the differential equations describing this circuit are identical to the general form of those describing a series RLC.

For the parallel circuit, the attenuation α is given by[18]

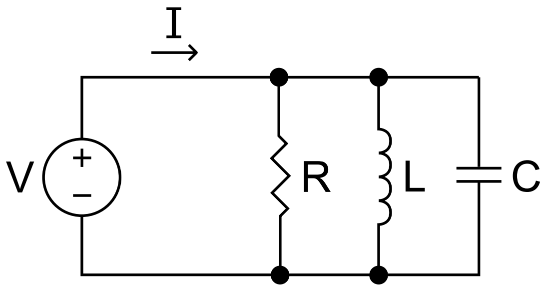


Figure 5. *RLC parallel circuit*
V *– the voltage source powering the circuit*
I *– the current admitted through the circuit*
R *– the equivalent resistance of the combined source, load, and components*
L *– the inductance of the inductor component*
C *– the capacitance of the capacitor component*

$$\alpha = \frac{1}{2RC}$$

and the damping factor is consequently

$$\zeta = \frac{1}{2R}\sqrt{\frac{L}{C}}$$

Likewise, the other scaled parameters, fractional bandwidth and Q are also reciprocals of each other. This means that a wide band, low Q circuit in one topology will become a narrow band, high Q circuit in the other topology when constructed from components with identical values. The fractional bandwidth and Q of the parallel circuit are given by

$$F_{\mathrm{b}} = \frac{1}{R}\sqrt{\frac{L}{C}}$$

and

$$Q = R\sqrt{\frac{C}{L}}\,.$$

Notice that the formulas here are the reciprocals of the formulas for the series circuit, given above.

Frequency domain

The complex admittance of this circuit is given by adding up the admittances of the components:

$$\frac{1}{Z} = \frac{1}{Z_L} + \frac{1}{Z_C} + \frac{1}{Z_R} = \frac{1}{j\omega L} + j\omega C + \frac{1}{R}$$

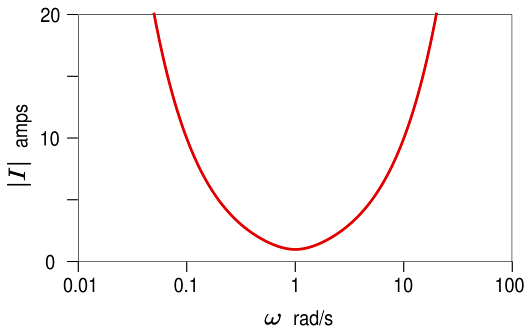


Figure 6. Sinusoidal steady-state analysis *normalised to* R = *1 ohm,* C = *1 farad,* L = *1 henry, and* V = *1.0 volt*

The change from a series arrangement to a parallel arrangement results in the circuit having a peak in impedance at resonance rather than a minimum, so the circuit is an antiresonator.

The graph opposite shows that there is a minimum in the frequency response of the current at the resonance frequency $\omega_0 = \frac{1}{\sqrt{LC}}$ when the circuit is driven by a constant voltage. On the other hand, if driven by a constant current, there would be a maximum in the voltage which would follow the same curve as the current in the series circuit.

4.3.4 Other configurations

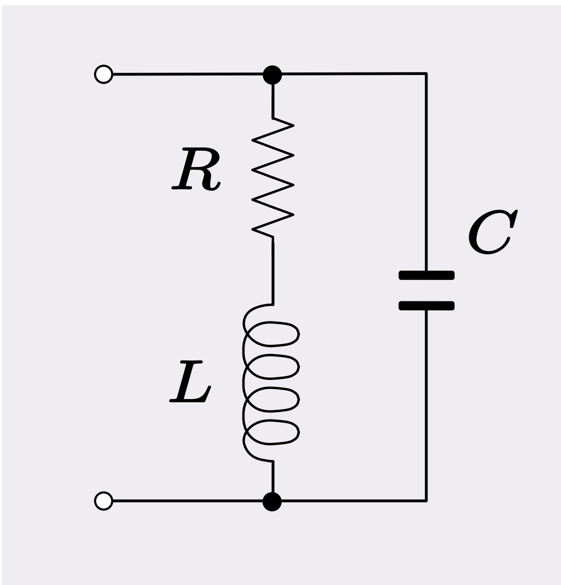


Fig. 7. *RLC parallel circuit with resistance in series with the inductor*

A series resistor with the inductor in a parallel LC circuit as shown in figure 7 is a topology commonly encountered where there is a need to take into account the resistance of the coil winding. Parallel LC circuits are frequently

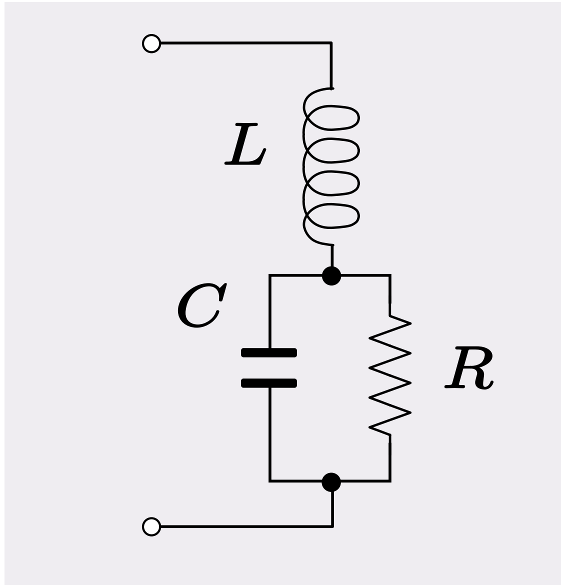


Fig. 8. *RLC series circuit with resistance in parallel with the capacitor*

used for bandpass filtering and the Q is largely governed by this resistance. The resonant frequency of this circuit is,[19]

$$\omega_0 = \sqrt{\frac{1}{LC} - \left(\frac{R}{L}\right)^2}$$

This is the resonant frequency of the circuit defined as the frequency at which the admittance has zero imaginary part. The frequency that appears in the generalised form of the characteristic equation (which is the same for this circuit as previously)

$$s^2 + 2\alpha s + {\omega'_0}^2 = 0$$

is not the same frequency. In this case it is the natural undamped resonant frequency[20]

$$\omega'_0 = \sqrt{\frac{1}{LC}}$$

The frequency ω_m at which the impedance magnitude is maximum is given by,[21]

$$\omega_m = \omega'_0 \sqrt{-\frac{1}{Q_L^2} + \sqrt{1 + \frac{2}{Q_L^2}}}$$

where $Q_L = \frac{1}{R}(\omega_0' L)$ is the quality factor of the coil. This can be well approximated by,[21]

$$\omega_m \approx \omega_0' \sqrt{1 - \frac{1}{2Q_L^4}}$$

Furthermore, the exact maximum impedance magnitude is given by,[21]

$$|Z|_{\text{max}} = RQ_L^2 \sqrt{\frac{1}{2Q_L\sqrt{Q_L^2+2} - 2Q_L^2 - 1}}$$

For values of Q_L greater than unity, this can be well approximated by,[21]

$$|Z|_{\text{max}} \approx RQ_L^2$$

In the same vein, a resistor in parallel with the capacitor in a series LC circuit can be used to represent a capacitor with a lossy dielectric. This configuration is shown in figure 8. The resonant frequency (frequency at which the impedance has zero imaginary part) in this case is given by,[22]

$$\omega_0 = \sqrt{\frac{1}{LC} - \frac{1}{(RC)^2}}$$

while the frequency ω_m at which the impedance magnitude is maximum is given by

$$\omega_m = \omega_0' \sqrt{-\frac{1}{Q_C^2} + \sqrt{1 + \frac{2}{Q_C^2}}}$$

where $Q_C = \omega_0' RC$

4.3.5 History

The first evidence that a capacitor could produce electrical oscillations was discovered in 1826 by French scientist Felix Savary.[23][24] He found that when a Leyden jar was discharged through a wire wound around an iron needle, sometimes the needle was left magnetized in one direction and sometimes in the opposite direction. He correctly deduced that this was caused by a damped oscillating discharge current in the wire, which reversed the magnetization of the needle back and forth until it was too small to have an effect, leaving the needle magnetized in a random direction.

American physicist Joseph Henry repeated Savary's experiment in 1842 and came to the same conclusion, apparently independently.[25][26] British scientist William Thomson (Lord Kelvin) in 1853 showed mathematically that the discharge of a Leyden jar through an inductance should be oscillatory, and derived its resonant frequency.[23][25][26]

British radio researcher Oliver Lodge, by discharging a large battery of Leyden jars through a long wire, created a tuned circuit with its resonant frequency in the audio range, which produced a musical tone from the spark when it was discharged.[25] In 1857 German physicist Berend Wilhelm Feddersen photographed the spark produced by a resonant Leyden jar circuit in a rotating mirror, providing visible evidence of the oscillations.[23][25][26] In 1868 Scottish physicist James Clerk Maxwell calculated the effect of applying an alternating current to a circuit with inductance and capacitance, showing that the response is maximum at the resonant frequency.[23]

The first example of an electrical resonance curve was published in 1887 by German physicist Heinrich Hertz in his pioneering paper on the discovery of radio waves, showing the length of spark obtainable from his spark-gap LC resonator detectors as a function of frequency.[23]

One of the first demonstrations of resonance between tuned circuits was Lodge's "syntonic jars" experiment around 1889[23][25] He placed two resonant circuits next to each other, each consisting of a Leyden jar connected to an adjustable one-turn coil with a spark gap. When a high voltage from an induction coil was applied to one tuned circuit, creating sparks and thus oscillating currents, sparks were excited in the other tuned circuit only when the inductors were adjusted to resonance. Lodge and some English scientists preferred the term "*syntony*" for this effect, but the term "*resonance*" eventually stuck.[23]

The first practical use for RLC circuits was in the 1890s in spark-gap radio transmitters to allow the receiver to be tuned to the transmitter. The first patent for a radio system that allowed tuning was filed by Lodge in 1897, although the first practical systems were invented in 1900 by Anglo Italian radio pioneer Guglielmo Marconi.[23]

4.3.6 Applications

Variable tuned circuits

A very frequent use of these circuits is in the tuning circuits of analogue radios. Adjustable tuning is commonly achieved with a parallel plate variable capacitor which allows the value of C to be changed and tune to stations on different frequencies. For the IF stage in the radio where the tuning is preset in the factory the more usual solution is an adjustable core in the inductor to adjust L. In this design the core (made of a high permeability material that has the effect of increasing inductance) is threaded so that it can be screwed further in, or screwed further out of the inductor winding as required.

Filters

In the filtering application, the resistor *R* becomes the load that the filter is working into. The value of the damping factor is chosen based on the desired bandwidth of the filter. For a wider bandwidth, a larger value of the damping factor is required (and vice versa). The three components give the designer three degrees of freedom. Two of these are required to set the bandwidth and resonant frequency. The designer is still left with one which can be used to scale *R*, *L* and *C* to convenient practical values. Alternatively, *R* may be predetermined by the external circuitry which will use the last degree of freedom.

Low-pass filter

An RLC circuit can be used as a low-pass filter. The circuit configuration is shown in figure 9. The corner frequency, that is, the frequency of the 3 dB point, is given by

$$\omega_{\mathrm{c}} = \frac{1}{\sqrt{LC}}$$

This is also the bandwidth of the filter. The damping factor is given by[27]

$$\zeta = \frac{1}{2R_{\mathrm{L}}}\sqrt{\frac{L}{C}}$$

High-pass filter

A high-pass filter is shown in figure 10. The corner frequency is the same as the low-pass filter

$$\omega_{\mathrm{c}} = \frac{1}{\sqrt{LC}}$$

The filter has a stop-band of this width.[28]

Band-pass filter

A band-pass filter can be formed with an RLC circuit by either placing a series LC circuit in series with the load resistor or else by placing a parallel LC circuit in parallel with the load resistor. These arrangements are shown in figures 11 and 12 respectively. The centre frequency is given by

$$\omega_{\mathrm{c}} = \frac{1}{\sqrt{LC}}$$

and the bandwidth for the series circuit is[29]

$$\Delta\omega = \frac{R_{\mathrm{L}}}{L}$$

The shunt version of the circuit is intended to be driven by a high impedance source, that is, a constant current source. Under those conditions the bandwidth is[29]

$$\Delta\omega = \frac{1}{CR_{\mathrm{L}}}$$

Band-stop filter

Figure 13 shows a band-stop filter formed by a series LC circuit in shunt across the load. Figure 14 is a band-stop filter formed by a parallel LC circuit in series with the load. The first case requires a high impedance source so that the current is diverted into the resonator when it becomes low impedance at resonance. The second case requires a low impedance source so that the voltage is dropped across the antiresonator when it becomes high impedance at resonance.[30]

Oscillators

For applications in oscillator circuits, it is generally desirable to make the attenuation (or equivalently, the damping factor) as small as possible. In practice, this objective requires making the circuit's resistance *R* as small as physically possible for a series circuit, or alternatively increasing *R* to as much as possible for a parallel circuit. In either case, the *RLC circuit* becomes a good approximation to an ideal LC circuit. However, for very low attenuation circuits (high Q-factor) circuits, issues such as dielectric losses of coils and capacitors can become important.

In an oscillator circuit

$$\alpha \ll \omega_0.$$

or equivalently

$$\zeta \ll 1.$$

As a result

$$\omega_d \approx \omega_0.$$

Voltage multiplier

In a series RLC circuit at resonance, the current is limited only by the resistance of the circuit

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

If R is small, consisting only of the inductor winding resistance say, then this current will be large. It will drop a voltage across the inductor of

$$V_{\mathrm{L}} = \frac{V}{R}\omega_0 L$$

An equal magnitude voltage will also be seen across the capacitor but in antiphase to the inductor. If R can be made sufficiently small, these voltages can be several times the input voltage. The voltage ratio is, in fact, the *Q* of the circuit,

$$\frac{V_{\mathrm{L}}}{V} = Q$$

A similar effect is observed with currents in the parallel circuit. Even though the circuit appears as high impedance to the external source, there is a large current circulating in the internal loop of the parallel inductor and capacitor.

Pulse discharge circuit

An overdamped series RLC circuit can be used as a pulse discharge circuit. Often it is useful to know the values of components that could be used to produce a waveform this is described by the form:

$$I(t) = I_0 \left(e^{-\alpha t} - e^{-\beta t}\right)$$

Such a circuit could consist of an energy storage capacitor, a load in the form of a resistance, some circuit inductance and a switch – all in series. The initial conditions are that the capacitor is at voltage, V_0 , and there is no current flowing in the inductor. If the inductance L is known, then the remaining parameters are given by the following – capacitance:

$$C = \frac{1}{L\alpha\beta}$$

Resistance (total of circuit and load):

$$R = L(\alpha + \beta)$$

Initial terminal voltage of capacitor:

$$V_0 = -I_0 L\alpha\beta \left(\frac{1}{\beta} - \frac{1}{\alpha}\right)$$

Rearranging for the case where *R* is known – Capacitance:

$$C = \frac{\alpha + \beta}{R\alpha\beta}$$

Inductance (total of circuit and load):

$$L = \frac{R}{\alpha + \beta}$$

Initial terminal voltage of capacitor:

$$V_0 = \frac{-I_0 R\alpha\beta}{\alpha + \beta} \left(\frac{1}{\beta} - \frac{1}{\alpha}\right)$$

4.3.7 See also

- RC circuit
- LC circuit
- RL circuit
- Electronic oscillator
- Linear circuit

4.3.8 References

[1] Kaiser, pp. 7.71–7.72.

[2] http://www.ece.ucsb.edu/Faculty/rodwell/Classes/ece218b/notes/Resonators.pdf

[3] Nilsson and Riedel, p. 308.

[4] Agarwal and Lang, p. 641.

[5] Agarwal and Lang, p. 646.

[6] Irwin, pp. 217–220.

[7] Agarwal and Lang, p. 656.

[8] Nilsson and Riedel, pp. 287–288.

[9] Irwin, p. 532.

[10] Agarwal and Lang, p. 648.

[11] Nilsson and Riedel, p. 295.

[12] Humar, pp. 223–224.

[13] Agarwal and Lang, p. 692.

[14] Nilsson and Riedel, p. 303.

[15] Irwin, p. 220.

[16] This section is based on Example 4.2.13 from Lokenath Debnath, Dambaru Bhatta, *Integral transforms and their applications*, 2nd ed. Chapman & Hall/CRC, 2007, ISBN 1-58488-575-0, pp. 198–202 (some notations have been changed to fit the rest of this article.)

[17] Kumar and Kumar, *Electric Circuits & Networks*, p. 464.

[18] Nilsson and Riedel, p. 286.

[19] Kaiser, pp. 5.26–5.27.

[20] Agarwal and Lang, p. 805.

[21] Cartwright, K. V.; Joseph, E.; Kaminsky, E. J. (2010). "Finding the exact maximum impedance resonant frequency of a practical parallel resonant circuit without calculus" (PDF). *The Technology Interface International Journal* **11** (1): 26–34.

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[23] Blanchard, Julian (October 1941). "The History of Electrical Resonance". *Bell System Technical Journal* (USA: American Telephone & Telegraph Co.) **20** (4): 415–. doi:10.1002/j.1538-7305.1941.tb03608.x. Retrieved 2013-02-25.

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[27] Kaiser, pp. 7.14–7.16.

[28] Kaiser, p. 7.21.

[29] Kaiser, pp. 7.21–7.27.

[30] Kaiser, pp. 7.30–7.34.

4.3.9 Bibliography

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- James William Nilsson, Susan A. Riedel, *Electric circuits*, Prentice Hall, 2008 ISBN 0-13-198925-1.

4.4 Low-pass filter

A **low-pass filter** is a filter that passes signals with a frequency lower than a certain cutoff frequency and attenuates signals with frequencies higher than the cutoff frequency. The amount of attenuation for each frequency depends on the filter design. The filter is sometimes called a **high-cut filter**, or **treble cut filter** in audio applications. A low-pass filter is the opposite of a high-pass filter. A band-pass filter is a combination of a low-pass and a high-pass filter.

Low-pass filters exist in many different forms, including electronic circuits (such as a *hiss filter* used in audio), anti-aliasing filters for conditioning signals prior to analog-to-digital conversion, digital filters for smoothing sets of data, acoustic barriers, blurring of images, and so on. The moving average operation used in fields such as finance is a particular kind of low-pass filter, and can be analyzed with the same signal processing techniques as are used for other low-pass filters. Low-pass filters provide a smoother form of a signal, removing the short-term fluctuations, and leaving the longer-term trend.

An optical filter with the same function can correctly be called a low-pass filter, but conventionally is called a *long-pass* filter (low frequency is long wavelength), to avoid confusion.

4.4.1 Examples

Acoustics

A stiff physical barrier tends to reflect higher sound frequencies, and so acts as a low-pass filter for transmitting sound. When music is playing in another room, the low notes are easily heard, while the high notes are attenuated.

Electronics

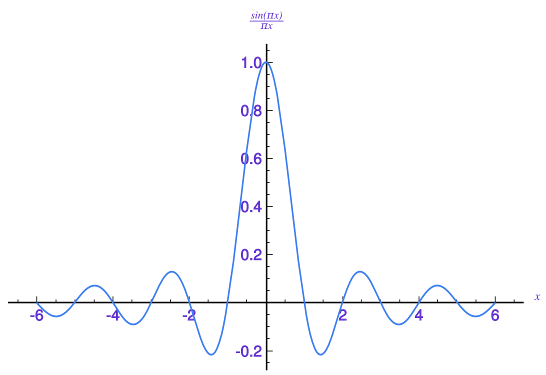
In an electronic low-pass RC filter for voltage signals, high frequencies in the input signal are attenuated, but the filter has little attenuation below the cutoff frequency determined by its RC time constant. For current signals, a similar circuit, using a resistor and capacitor in parallel, works in a similar manner. (See current divider discussed in more detail below.)

Electronic low-pass filters are used on inputs to subwoofers and other types of loudspeakers, to block high pitches that they can't efficiently reproduce. Radio transmitters use low-pass filters to block harmonic emissions that might interfere with other communications. The tone knob on many electric guitars is a low-pass filter used to reduce the amount of treble in the sound. An integrator is another time constant low-pass filter.[1]

Telephone lines fitted with DSL splitters use low-pass and high-pass filters to separate DSL and POTS signals sharing the same pair of wires.[2][3]

Low-pass filters also play a significant role in the sculpting of sound created by analogue and virtual analogue synthesisers. *See subtractive synthesis.*

4.4.2 Ideal and real filters



The sinc function, the impulse response of an ideal low-pass filter.

An ideal low-pass filter completely eliminates all frequencies above the cutoff frequency while passing those below unchanged; its frequency response is a rectangular function and is a brick-wall filter. The transition region present in practical filters does not exist in an ideal filter. An ideal low-pass filter can be realized mathematically (theoretically) by multiplying a signal by the rectangular function in the frequency domain or, equivalently, convolution with its impulse response, a sinc function, in the time domain.

However, the ideal filter is impossible to realize without also having signals of infinite extent in time, and so generally needs to be approximated for real ongoing signals, because the sinc function's support region extends to all past and future times. The filter would therefore need to have infinite delay, or knowledge of the infinite future and past, in order to perform the convolution. It is effectively realizable for pre-recorded digital signals by assuming extensions of zero into the past and future, or more typically by making the signal repetitive and using Fourier analysis.

Real filters for real-time applications approximate the ideal filter by truncating and windowing the infinite impulse response to make a finite impulse response; applying that filter requires delaying the signal for a moderate period of time, allowing the computation to “see” a little bit into the future. This delay is manifested as phase shift. Greater accuracy in approximation requires a longer delay.

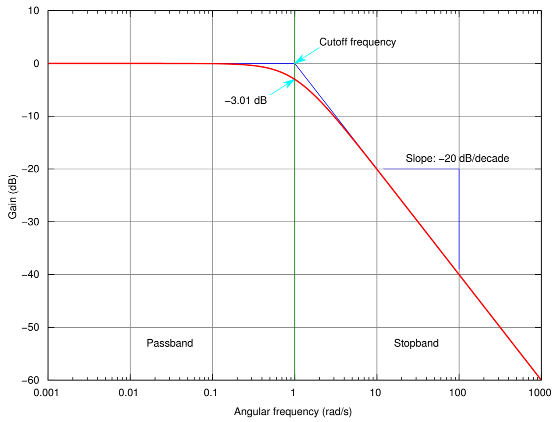
An ideal low-pass filter results in ringing artifacts via the Gibbs phenomenon. These can be reduced or worsened by choice of windowing function, and the design and choice of real filters involves understanding and minimizing these artifacts. For example, “simple truncation [of sinc] causes severe ringing artifacts,” in signal reconstruction, and to reduce these artifacts one uses window functions “which drop off more smoothly at the edges.”[4]

The Whittaker–Shannon interpolation formula describes how to use a perfect low-pass filter to reconstruct a continuous signal from a sampled digital signal. Real digital-to-analog converters use real filter approximations.

4.4.3 Continuous-time low-pass filters

There are many different types of filter circuits, with different responses to changing frequency. The frequency response of a filter is generally represented using a Bode plot, and the filter is characterized by its cutoff frequency and rate of frequency rolloff. In all cases, at the *cutoff frequency,* the filter attenuates the input power by half or 3 dB. So the **order** of the filter determines the amount of additional attenuation for frequencies higher than the cutoff frequency.

- A **first-order filter**, for example, reduces the signal amplitude by half (so power reduces by a factor of 4, or 6 dB), every time the frequency doubles (goes up one octave); more precisely, the power rolloff approaches 20 dB per decade in the limit of high frequency. The magnitude Bode plot for a first-order filter looks like a horizontal line below the cutoff frequency, and a diagonal line above the cutoff fre-



The gain-magnitude frequency response of a first-order (one-pole) low-pass filter. Power gain *is shown in decibels (i.e., a 3 dB decline reflects an additional half-power attenuation). Angular frequency is shown on a logarithmic scale in units of radians per second.*

quency. There is also a "knee curve" at the boundary between the two, which smoothly transitions between the two straight line regions. If the transfer function of a first-order low-pass filter has a zero as well as a pole, the Bode plot flattens out again, at some maximum attenuation of high frequencies; such an effect is caused for example by a little bit of the input leaking around the one-pole filter; this one-pole–one-zero filter is still a first-order low-pass. *See Pole–zero plot and RC circuit.*

- A **second-order filter** attenuates high frequencies more steeply. The Bode plot for this type of filter resembles that of a first-order filter, except that it falls off more quickly. For example, a second-order Butterworth filter reduces the signal amplitude to one fourth its original level every time the frequency doubles (so power decreases by 12 dB per octave, or 40 dB per decade). Other all-pole second-order filters may roll off at different rates initially depending on their Q factor, but approach the same final rate of 12 dB per octave; as with the first-order filters, zeroes in the transfer function can change the high-frequency asymptote. See RLC circuit.
- Third- and higher-order filters are defined similarly. In general, the final rate of power rolloff for an order- n all-pole filter is $6n$ dB per octave (i.e., $20n$ dB per decade).

On any Butterworth filter, if one extends the horizontal line to the right and the diagonal line to the upper-left (the asymptotes of the function), they intersect at exactly the *cutoff frequency*. The frequency response at the cutoff frequency in a first-order filter is 3 dB below the horizontal line. The various types of filters (Butterworth filter, Chebyshev filter, Bessel filter, etc.) all have different-looking *knee curves*. Many second-order filters have "peaking" or resonance that puts their frequency response at the cutoff frequency *above* the horizontal line. Furthermore, the actual frequency where this peaking occurs can be predicted without calculus, as shown by Cartwright[5] et al. For third-order filters, the peaking and its frequency of occurrence can too be predicted without calculus as recently shown by Cartwright[6] et al. *See electronic filter for other types.*

The meanings of 'low' and 'high'—that is, the cutoff frequency—depend on the characteristics of the filter. The term "low-pass filter" merely refers to the shape of the filter's response; a high-pass filter could be built that cuts off at a lower frequency than any low-pass filter—it is their responses that set them apart. Electronic circuits can be devised for any desired frequency range, right up through microwave frequencies (above 1 GHz) and higher.

Laplace notation

Continuous-time filters can also be described in terms of the Laplace transform of their impulse response, in a way that lets all characteristics of the filter be easily analyzed by considering the pattern of poles and zeros of the Laplace transform in the complex plane. (In discrete time, one can similarly consider the Z-transform of the impulse response.)

For example, a first-order low-pass filter can be described in Laplace notation as:

$$\frac{\text{Output}}{\text{Input}} = K\frac{1}{\tau s + 1}$$

where s is the Laplace transform variable, τ is the filter time constant, and K is the gain of the filter in the passband .

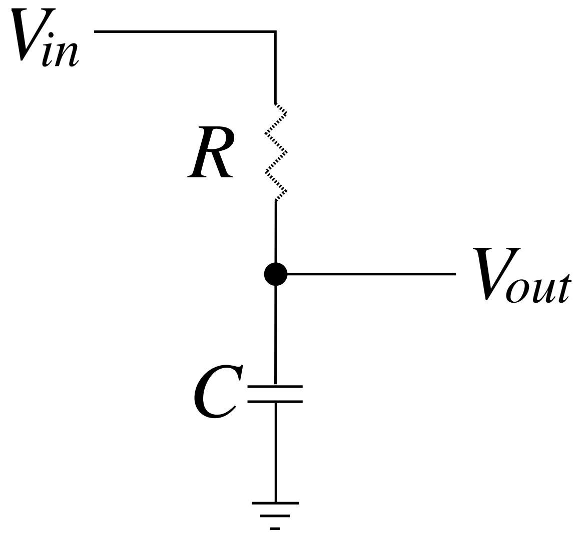
4.4.4 Electronic low-pass filters

First order

RC filter One simple low-pass filter circuit consists of a resistor in series with a load, and a capacitor in parallel with the load. The capacitor exhibits reactance, and blocks low-frequency signals, forcing them through the load instead. At higher frequencies the reactance drops, and the capacitor effectively functions as a short circuit. The combination of resistance and capacitance gives the time constant of the filter $\tau = RC$ (represented by the Greek letter tau). The break frequency, also called the turnover frequency or cutoff frequency (in hertz), is determined by the time constant:

$$f_c = \frac{1}{2\pi\tau} = \frac{1}{2\pi RC}$$

or equivalently (in radians per second):



Passive, first order low-pass RC filter

$$\omega_c = \frac{1}{\tau} = \frac{1}{RC}$$

This circuit may be understood by considering the time the capacitor needs to charge or discharge through the resistor:

- At low frequencies, there is plenty of time for the capacitor to charge up to practically the same voltage as the input voltage.
- At high frequencies, the capacitor only has time to charge up a small amount before the input switches direction. The output goes up and down only a small fraction of the amount the input goes up and down. At double the frequency, there's only time for it to charge up half the amount.

Another way to understand this circuit is through the concept of reactance at a particular frequency:

- Since direct current (DC) cannot flow through the capacitor, DC input must flow out the path marked V_{out} (analogous to removing the capacitor).
- Since alternating current (AC) flows very well through the capacitor, almost as well as it flows through solid wire, AC input flows out through the capacitor, effectively short circuiting to ground (analogous to replacing the capacitor with just a wire).

The capacitor is not an "on/off" object (like the block or pass fluidic explanation above). The capacitor variably acts between these two extremes. It is the Bode plot and frequency response that show this variability.

RL filter Main article: RL filter

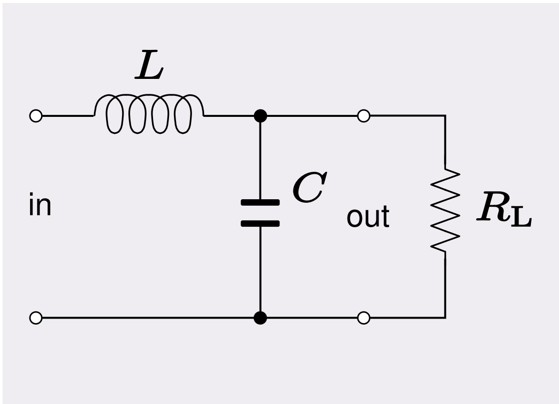
A resistor–inductor circuit or RL filter is an electric circuit composed of resistors and inductors driven by a voltage or current source. A first order RL circuit is composed of one resistor and one inductor and is the simplest type of RL circuit.

A first order RL circuit is one of the simplest analogue infinite impulse response electronic filters. It consists of a resistor and an inductor, either in series driven by a voltage source or in parallel driven by a current source.

Second order

RLC filter Main article: RLC circuit

An RLC circuit (the letters R, L and C can be in other

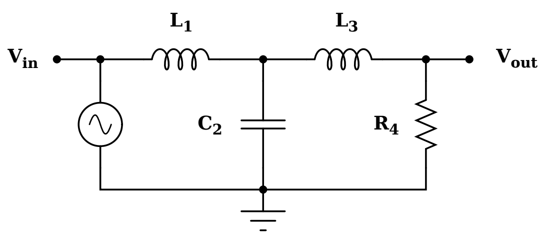


RLC circuit as a low-pass filter

orders) is an electrical circuit consisting of a resistor, an inductor, and a capacitor, connected in series or in parallel. The RLC part of the name is due to those letters being the usual electrical symbols for resistance, inductance and capacitance respectively. The circuit forms a harmonic oscillator for current and will resonate in a similar way as an LC circuit will. The main difference that the presence of the resistor makes is that any oscillation induced in the circuit will die away over time if it is not kept going by a source. This effect of the resistor is called damping. The presence of the resistance also reduces the peak resonant frequency somewhat. Some resistance is unavoidable in real circuits, even if a resistor is not specifically included as a component. An ideal, pure LC circuit is an abstraction for the purpose of theory.

There are many applications for this circuit. They are used in many different types of oscillator circuits. Another important application is for tuning, such as in radio receivers or television sets, where they are used to select a narrow range of frequencies from the ambient radio waves. In this role the circuit is often referred to as a tuned circuit. An RLC circuit can be used as a band-pass filter, band-stop filter, low-pass filter or high-pass filter. The RLC filter is described as a *second-order* circuit, meaning that any voltage or current in the circuit can be described by a second-order differential equation in circuit analysis.

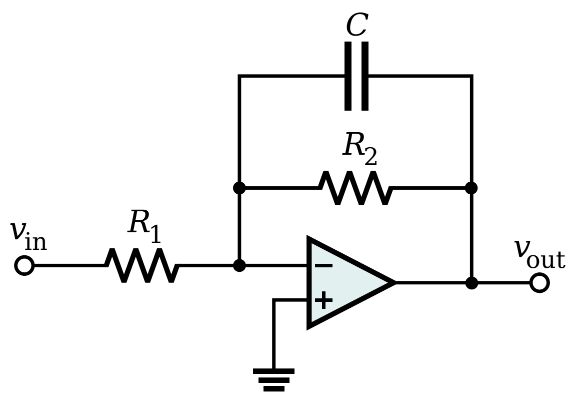
Higher order passive filters



A third-order low-pass filter (Cauer topology). The filter becomes a Butterworth filter with cutoff frequency ωc=1 when (for example) C_2=4/3 farad, R_4=1 ohm, L_1=3/2 henry and L_3=1/2 henry.

Higher order passive filters, can also be constructed (see diagram for a third order example).

Active electronic realization



An active low-pass filter

Another type of electrical circuit is an *active* low-pass filter.

In the operational amplifier circuit shown in the figure, the cutoff frequency (in hertz) is defined as:

$$f_c = \frac{1}{2\pi R_2 C}$$

or equivalently (in radians per second):

$$\omega_c = \frac{1}{R_2 C}$$

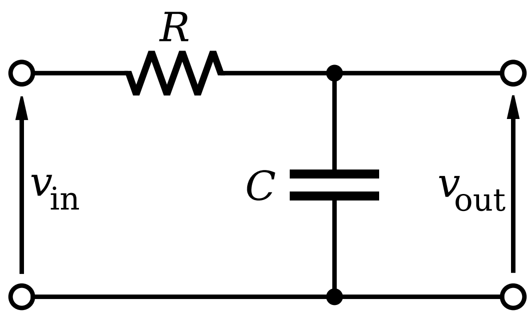
The gain in the passband is $-R_2/R_1$, and the stopband drops off at −6 dB per octave (that is −20 dB per decade) as it is a first-order filter.

Discrete-time realization

For another method of conversion from continuous- to discrete-time, see Bilinear transform.

Many digital filters are designed to give low-pass characteristics. Both infinite impulse response and finite impulse response low pass filters as well as filters using Fourier transforms are widely used.

Simple infinite impulse response filter The effect of an infinite impulse response low-pass filter can be simulated on a computer by analyzing an RC filter's behavior in the time domain, and then discretizing the model.



A simple low-pass RC filter

From the circuit diagram to the right, according to Kirchhoff's Laws and the definition of capacitance:

where $Q_c(t)$ is the charge stored in the capacitor at time t. Substituting equation **Q** into equation **I** gives $i(t) = C\frac{\mathrm{d}\,v_{\text{out}}}{\mathrm{d}\,t}$, which can be substituted into equation **V** so that:

$$v_{\text{in}}(t) - v_{\text{out}}(t) = RC\frac{\mathrm{d}\,v_{\text{out}}}{\mathrm{d}\,t}$$

This equation can be discretized. For simplicity, assume that samples of the input and output are taken at evenly spaced points in time separated by Δ_T time. Let the samples of v_{in} be represented by the sequence $(x_1, x_2, ..., x_n)$, and let v_{out} be represented by the sequence $(y_1, y_2, ..., y_n)$, which correspond to the same points in time. Making these substitutions:

$$x_i - y_i = RC\,\frac{y_i - y_{i-1}}{\Delta_T}$$

And rearranging terms gives the recurrence relation

$$y_i = \overbrace{x_i \left(\frac{\Delta_T}{RC + \Delta_T} \right)}^{\text{contribution Input}} + \overbrace{y_{i-1} \left(\frac{RC}{RC + \Delta_T} \right)}^{\text{output previous from Inertia}}.$$

That is, this discrete-time implementation of a simple RC low-pass filter is the exponentially weighted moving average

$$y_i = \alpha x_i + (1-\alpha) y_{i-1} \qquad \text{where} \qquad \alpha \triangleq \frac{\Delta_T}{RC + \Delta_T}$$

By definition, the *smoothing factor* $0 \le \alpha \le 1$. The expression for α yields the equivalent time constant RC in terms of the sampling period Δ_T and smoothing factor α :

$$RC = \Delta_T \left(\frac{1-\alpha}{\alpha} \right)$$

Recalling that

$$f_c = \frac{1}{2\pi RC} \text{ so } RC = \frac{1}{2\pi f_c}$$

then α and f_c are related by:

$$\alpha = \frac{2\pi \Delta_T f_c}{2\pi \Delta_T f_c + 1}$$

and

$$f_c = \frac{\alpha}{(1-\alpha) 2\pi \Delta_T}$$

If $\alpha = 0.5$, then the RC time constant is equal to the sampling period. If $\alpha \ll 0.5$, then RC is significantly larger than the sampling interval, and $\Delta_T \approx \alpha RC$.

The filter recurrence relation provides a way to determine the output samples in terms of the input samples and the preceding output. The following pseudocode algorithm simulates the effect of a low-pass filter on a series of digital samples:

// Return RC low-pass filter output samples, given input samples, // time interval *dt*, and time constant *RC* **function** lowpass(*real[0..n]* x, *real* dt, *real* RC) **var** *real[0..n]* y **var** *real* α := dt / (RC + dt) y[0] := x[0] **for** i **from** 1 **to** n y[i] := α * x[i] + (1-α) * y[i-1] **return** y

The loop that calculates each of the *n* outputs can be refactored into the equivalent:

for i **from** 1 **to** n y[i] := y[i-1] + α * (x[i] - y[i-1])

That is, the change from one filter output to the next is proportional to the difference between the previous output and the next input. This exponential smoothing property matches the exponential decay seen in the continuous-time system. As expected, as the time constant RC increases, the discrete-time smoothing parameter α decreases, and the output samples $(y_1, y_2, \ldots, y_n)$ respond more slowly to a change in the input samples $(x_1, x_2, \ldots, x_n)$; the system has more *inertia*. This filter is an infinite-impulse-response (IIR) single-pole low-pass filter.

Finite impulse response Finite-impulse-response filters can be built that approximate to the sinc function time-domain response of an ideal sharp-cutoff low-pass filter. In practice, the time-domain response must be time truncated and is often of a simplified shape; in the simplest case, a running average can be used, giving a square time response.[7]

Fourier transformation For minimum distortion the finite impulse response filter has an unbounded number of coefficients.

For non-realtime filtering, to achieve a low pass filter, the entire signal is usually taken as a looped signal, the Fourier transform is taken, filtered in the frequency domain, followed by an inverse Fourier transform. Only O(n log(n)) operations are required compared to O(n^2) for the time domain filtering algorithm.

This can also sometimes be done in real-time, where the signal is delayed long enough to perform the Fourier transformation on shorter, overlapping blocks.

4.4.5 See also

- Baseband
- DSL filter

4.4.6 References

[1] Sedra, Adel; Smith, Kenneth C. (1991). *Microelectronic Circuits, 3 ed.* Saunders College Publishing. p. 60. ISBN 0-03-051648-X.

[2] "ADSL filters explained". Epanorama.net. Retrieved 2013-09-24.

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[5] K. V. Cartwright, P. Russell and E. J. Kaminsky,"Finding the maximum magnitude response (gain) of second-order filters without calculus," Lat. Am. J. Phys. Educ. Vol. 6, No. 4, pp. 559-565, 2012.

[6] Cartwright, K. V.; P. Russell; E. J. Kaminsky (2013). "Finding the maximum and minimum magnitude responses (gains) of third-order filters without calculus" (PDF). *Lat. Am. J. Phys. Educ.* **7** (4): 582–587.

[7] Signal recovery from noise in electronic instrumentation – T H Whilmshurst

4.4.7 External links

- Low-pass filter
- Low Pass Filter java simulator
- ECE 209: Review of Circuits as LTI Systems, a short primer on the mathematical analysis of (electrical) LTI systems.
- ECE 209: Sources of Phase Shift, an intuitive explanation of the source of phase shift in a low-pass filter. Also verifies simple passive LPF transfer function by means of trigonometric identity.

4.5 High-pass filter

This article is about an electronic component. For the Australian band, see High Pass Filter (band).

A **high-pass filter** is an electronic filter that passes signals with a frequency higher than a certain cutoff frequency and attenuates signals with frequencies lower than the cutoff frequency. The amount of attenuation for each frequency depends on the filter design. A high-pass filter is usually modeled as a linear time-invariant system. It is sometimes called a **low-cut filter** or **bass-cut filter**.[1] High-pass filters have many uses, such as blocking DC from circuitry sensitive to non-zero average voltages or radio frequency devices. They can also be used in conjunction with a low-pass filter to produce a bandpass filter.

4.5.1 First-order continuous-time implementation

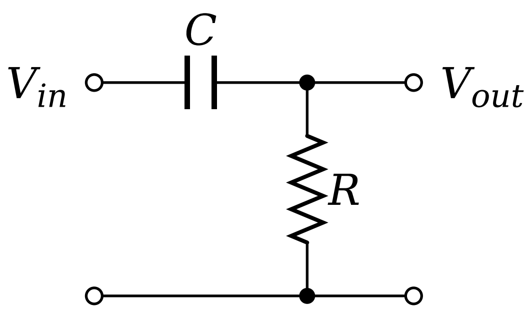


Figure 1: A passive, analog, first-order high-pass filter, realized by an RC circuit

The simple first-order electronic high-pass filter shown in Figure 1 is implemented by placing an input voltage across the series combination of a capacitor and a resistor and using the voltage across the resistor as an output. The product of the resistance and capacitance ($R \times C$) is the time constant (τ); it is inversely proportional to the cutoff frequency fc, that is,

$$f_c = \frac{1}{2\pi\tau} = \frac{1}{2\pi RC},$$

where fc is in hertz, τ is in seconds, R is in ohms, and C is in farads.

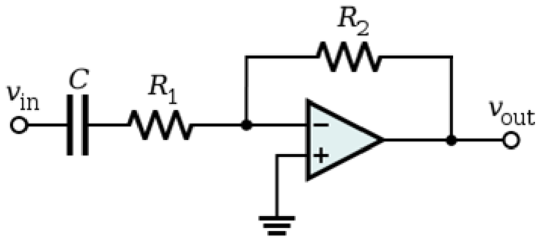


Figure 2: An active high-pass filter

Figure 2 shows an active electronic implementation of a first-order high-pass filter using an operational amplifier. In this case, the filter has a passband gain of -R_2/R_1 and has a cutoff frequency of

$$f_c = \frac{1}{2\pi\tau} = \frac{1}{2\pi R_1 C},$$

Because this filter is active, it may have non-unity passband gain. That is, high-frequency signals are inverted and amplified by R_2/R_1.

4.5.2 Discrete-time realization

For another method of conversion from continuous- to discrete-time, see Bilinear transform.

Discrete-time high-pass filters can also be designed. Discrete-time filter design is beyond the scope of this article; however, a simple example comes from the conversion of the continuous-time high-pass filter above to a discrete-time realization. That is, the continuous-time behavior can be discretized.

From the circuit in Figure 1 above, according to Kirchhoff's Laws and the definition of capacitance:

$$\begin{cases} V_{\text{out}}(t) = I(t)\,R & \text{(V)} \\ Q_c(t) = C\,\left(V_{\text{in}}(t) - V_{\text{out}}(t)\right) & \text{(Q)} \\ I(t) = \frac{\mathrm{d}\,Q_c}{\mathrm{d}\,t} & \text{(I)} \end{cases}$$

where $Q_c(t)$ is the charge stored in the capacitor at time t . Substituting Equation (Q) into Equation (I) and then Equation (I) into Equation (V) gives:

$$V_{\text{out}}(t) = \overbrace{C\left(\frac{\mathrm{d}\,V_{\text{in}}}{\mathrm{d}\,t} - \frac{\mathrm{d}\,V_{\text{out}}}{\mathrm{d}\,t}\right)}^{I(t)} R = RC\left(\frac{\mathrm{d}\,V_{\text{in}}}{\mathrm{d}\,t} - \frac{\mathrm{d}\,V_{\text{out}}}{\mathrm{d}\,t}\right)$$

This equation can be discretized. For simplicity, assume that samples of the input and output are taken at evenly spaced points in time separated by Δ_T time. Let the samples of V_{in} be represented by the sequence $(x_1, x_2, \ldots, x_n)$, and let V_{out} be represented by the sequence $(y_1, y_2, \ldots, y_n)$ which correspond to the same points in time. Making these substitutions:

$$y_i = RC\left(\frac{x_i - x_{i-1}}{\Delta_T} - \frac{y_i - y_{i-1}}{\Delta_T}\right)$$

And rearranging terms gives the recurrence relation

$$y_i = \overbrace{\frac{RC}{RC + \Delta_T} y_{i-1}}^{\text{inputs prior from contribution Decaying}} + \overbrace{\frac{RC}{RC + \Delta_T}(x_i - x_{i-1})}^{\text{input in change from Contribution}}$$

That is, this discrete-time implementation of a simple continuous-time RC high-pass filter is

$$y_i = \alpha y_{i-1} + \alpha(x_i - x_{i-1}) \qquad \text{where} \qquad \alpha \triangleq \frac{RC}{RC + \Delta_T}$$

By definition, $0 \le \alpha \le 1$. The expression for parameter α yields the equivalent time constant RC in terms of the sampling period Δ_T and α :

$$RC = \Delta_T\left(\frac{\alpha}{1-\alpha}\right)$$

Recalling that

$f_c = \frac{1}{2\pi RC}$ so $RC = \frac{1}{2\pi f_c}$

then α and f_c are related by:

$$\alpha = \frac{1}{2\pi \Delta_T f_c + 1}$$

and

$$f_c = \frac{1-\alpha}{2\pi\alpha\Delta_T}$$

If $\alpha = 0.5$, then the RC time constant equal to the sampling period. If $\alpha \ll 0.5$, then RC is significantly smaller than the sampling interval, and $RC \approx \alpha\Delta_T$.

Algorithmic implementation

The filter recurrence relation provides a way to determine the output samples in terms of the input samples and the preceding output. The following pseudocode algorithm will simulate the effect of a high-pass filter on a series of digital samples:

// Return RC high-pass filter output samples, given input samples, // time interval *dt*, and time constant *RC* **function** highpass(*real[0..n]* x, *real* dt, *real* RC) **var** *real[0..n]* y **var** *real* α := RC / (RC + dt) y[0] := x[0] **for** i **from** 1 **to** n y[i] := α * y[i-1] + α * (x[i] - x[i-1]) **return** y

The loop which calculates each of the n outputs can be refactored into the equivalent:

for i **from** 1 **to** n y[i] := α * (y[i-1] + x[i] - x[i-1])

However, the earlier form shows how the parameter α changes the impact of the prior output y[i-1] and current *change* in input (x[i] - x[i-1]). In particular,

- A large α implies that the output will decay very slowly but will also be strongly influenced by even small changes in input. By the relationship between parameter α and time constant RC above, a large α corresponds to a large RC and therefore a low corner frequency of the filter. Hence, this case corresponds to a high-pass filter with a very narrow stop band. Because it is excited by small changes and tends to hold its prior output values for a long time, it can pass relatively low frequencies. However, a constant input (i.e., an input with (x[i] - x[i-1])=0) will always decay to zero, as would be expected with a high-pass filter with a large RC .
- A small α implies that the output will decay quickly and will require large changes in the input (i.e., (x[i] - x[i-1]) is large) to cause the output to change much. By the relationship between parameter α and time constant RC above, a small α corresponds to a small RC and therefore a high corner frequency of the filter. Hence, this case corresponds to a high-pass filter with a very wide stop band. Because it requires large (i.e., fast) changes and tends to quickly forget its prior output values, it can only pass relatively high frequencies, as would be expected with a high-pass filter with a small RC .

4.5.3 Applications

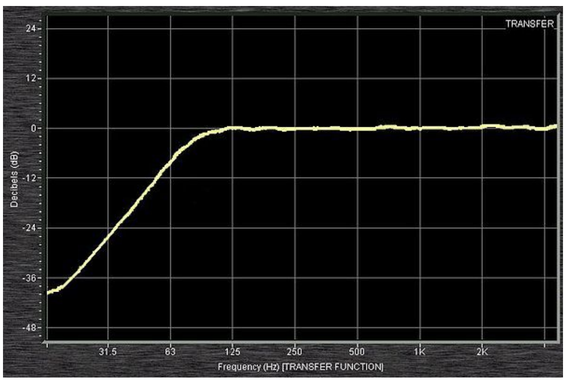
Audio

High-pass filters have many applications. They are used as part of an audio crossover to direct high frequencies to a tweeter while attenuating bass signals which could interfere with, or damage, the speaker. When such a filter is built into a loudspeaker cabinet it is normally a passive filter that also includes a low-pass filter for the woofer and so often employs both a capacitor and inductor (although very simple high-pass filters for tweeters can consist of a series capacitor and nothing else). As an example, the formula above, applied to a tweeter with R=10 Ohm, will determine the capacitor value for a cut-off frequency of 5 kHz. $C = \frac{1}{2\pi f R} = \frac{1}{6.28 \times 5000 \times 10} = 3.18 \times 10^{-6}$, or approx 3.2 µF.

An alternative, which provides good quality sound without inductors (which are prone to parasitic coupling, are expensive, and may have significant internal resistance) is to employ bi-amplification with active RC filters or active digital filters with separate power amplifiers for each loudspeaker. Such low-current and low-voltage line level crossovers are called active crossovers.[1]

Rumble filters are high-pass filters applied to the removal of unwanted sounds near to the lower end of the audible range or below. For example, noises (e.g., footsteps, or motor noises from record players and tape decks) may be removed because they are undesired or may overload the RIAA equalization circuit of the preamp.[1]

High-pass filters are also used for AC coupling at the inputs of many audio power amplifiers, for preventing the amplification of DC currents which may harm the amplifier, rob the amplifier of headroom, and generate waste heat at the loudspeakers voice coil. One amplifier, the professional audio model DC300 made by Crown International beginning in the 1960s, did not have high-pass filtering at all, and could be used to amplify the DC signal of a common 9-volt battery at the input to supply 18 volts DC in an emergency for mixing console power.[2] However, that model's basic design has been superseded by newer designs such as the Crown Macro-Tech series developed in the late 1980s which included 10 Hz high-pass filtering on the inputs and switchable 35 Hz high-pass filtering on the outputs.[3] Another example is the QSC Audio PLX amplifier series which includes an internal 5 Hz high-pass filter which is applied to the inputs whenever the optional 50 and 30 Hz high-pass filters are turned off.[4]



A 75 Hz "low cut" filter from an input channel of a Mackie 1402 mixing console as measured by Smaart software. This high-pass filter has a slope of 18 dB per octave.

Mixing consoles often include high-pass filtering at each channel strip. Some models have fixed-slope, fixed-frequency high-pass filters at 80 or 100 Hz that can be engaged; other models have sweepable high-pass filters, filters of fixed slope that can be set within a specified frequency range, such as from 20 to 400 Hz on the Midas Heritage 3000, or 20 to 20,000 Hz on the Yamaha M7CL digital mixing console. Veteran systems engineer and live sound mixer Bruce Main recommends that high-pass filters be engaged for most mixer input sources, except for those such as kick drum, bass guitar and piano, sources which will have useful low frequency sounds. Main writes that DI unit inputs (as opposed to microphone inputs) do not need high-pass filtering as they are not subject to modulation by low-frequency stage wash—low frequency sounds coming from the subwoofers or the public address system and wrapping around to the stage. Main indicates that high-pass filters are commonly used for directional microphones which have a proximity effect—a low-frequency boost for very close sources. This low frequency boost commonly causes problems up to 200 or 300 Hz, but Main notes that he has seen microphones that benefit from a 500 Hz high-pass filter setting on the console.[5]

Image

Example of high-pass filter applied to the right half of a photograph. Left side is unmodified, Right side is with a high-pass filter applied (in this case, with a radius of 4.9)

High-pass and low-pass filters are also used in digital image processing to perform image modifications, enhancements, noise reduction, etc., using designs done in either the spatial domain or the frequency domain.[6]

A high-pass filter, if the imaging software does not have one, can be done by duplicating the layer, putting a gaussian blur, inverting, and then blending with the original layer using an opacity (say 50%) with the original layer.[7]

The unsharp masking, or sharpening, operation used in image editing software is a high-boost filter, a generalization of high-pass.

4.5.4 See also

- DSL filter
- Band-stop filter
- Bias tee
- Differentiator

4.5.5 References

[1] Watkinson, John (1998). *The Art of Sound Reproduction*. Focal Press. pp. 268, 479. ISBN 0-240-51512-9. Retrieved March 9, 2010.

[2] Andrews, Keith; posting as ssltech (January 11, 2010). "Re: Running the board for a show this big?". *Recording, Engineering & Production*. ProSoundWeb. Retrieved 9 March 2010.

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[5] Main, Bruce (February 16, 2010). "Cut 'Em Off At The Pass: Effective Uses Of High-Pass Filtering". *Live Sound International* (Framingham, Massachusetts: ProSoundWeb, EH Publishing).

[6] Paul M. Mather (2004). *Computer processing of remotely sensed images: an introduction* (3rd ed.). John Wiley and Sons. p. 181. ISBN 978-0-470-84919-4.

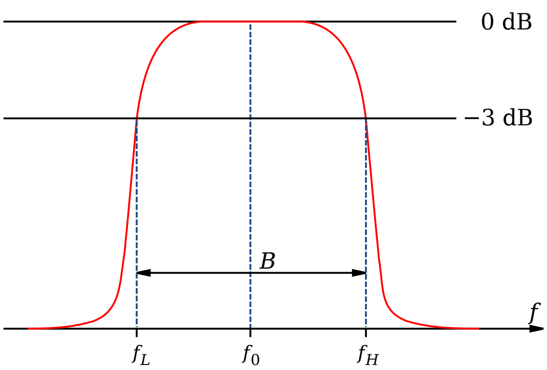
[7] "Gimp tutorial with high-pass filter operation".

4.5.6 External links

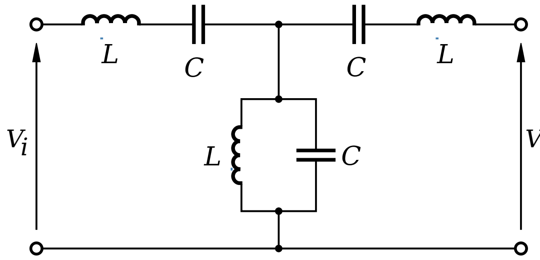
- Common Impulse Responses
- ECE 209: Review of Circuits as LTI Systems, a short primer on the mathematical analysis of (electrical) LTI systems.
- ECE 209: Sources of Phase Shift, an intuitive explanation of the source of phase shift in a high-pass filter. Also verifies simple passive LPF transfer function by means of trigonometric identity.

4.6 Band-pass filter

A **band-pass filter** is a device that passes frequencies within a certain range and rejects (attenuates) frequencies outside that range.



Bandwidth measured at half-power points (gain −3 dB, √2/2, or about 0.707 relative to peak) on a diagram showing magnitude transfer function versus frequency for a band-pass filter.



A medium-complexity example of a band-pass filter.

4.6.1 Description

An example of an analogue electronic band-pass filter is an RLC circuit (a resistor–inductor–capacitor circuit). These filters can also be created by combining a low-pass filter with a high-pass filter.[1]

Bandpass is an adjective that describes a type of filter or filtering process; it is to be distinguished from passband, which refers to the actual portion of affected spectrum. Hence, one might say "A dual bandpass filter has two passbands." A *bandpass signal* is a signal containing a band of frequencies not adjacent to zero frequency, such as a signal that comes out of a bandpass filter.[2]

An ideal bandpass filter would have a completely flat passband (e.g. with no gain/attenuation throughout) and would completely attenuate all frequencies outside the passband. Additionally, the transition out of the passband would have brickwall characteristics.

In practice, no bandpass filter is ideal. The filter does not attenuate all frequencies outside the desired frequency range completely; in particular, there is a region just outside the intended passband where frequencies are attenuated, but not rejected. This is known as the filter roll-off, and it is usually expressed in dB of attenuation per octave or decade of frequency. Generally, the design of a filter seeks to make the roll-off as narrow as possible, thus allowing the filter to perform as close as possible to its intended design. Often, this is achieved at the expense of pass-band or stop-band *ripple*.

The bandwidth of the filter is simply the difference between the upper and lower cutoff frequencies. The shape factor is the ratio of bandwidths measured using two different attenuation values to determine the cutoff frequency, e.g., a shape factor of 2:1 at 30/3 dB means the bandwidth measured between frequencies at 30 dB attenuation is twice that measured between frequencies at 3 dB attenuation.

Optical band-pass filters are common in photography and theatre lighting work. These filters take the form of a transparent coloured film or sheet.

4.6.2 Q factor

A band-pass filter can be characterised by its Q factor. The Q-factor is the inverse of the fractional bandwidth. A high-Q filter will have a narrow passband and a low-Q filter will have a wide passband. These are respectively referred to as narrow-band and wide-band filters.

4.6.3 Applications

Bandpass filters are widely used in wireless transmitters and receivers. The main function of such a filter in a transmitter is to limit the bandwidth of the output signal to the band allocated for the transmission. This prevents the transmitter from interfering with other stations. In a receiver, a bandpass filter allows signals within a selected range of frequencies to be heard or decoded, while preventing signals at unwanted frequencies from getting through. A bandpass filter also optimizes the signal-to-noise ratio and sensitivity of a receiver.

In both transmitting and receiving applications, well-designed bandpass filters, having the optimum bandwidth for the mode and speed of communication being used, maximize the number of signal transmitters that can exist in a system, while minimizing the interference or competition among signals.

Outside of electronics and signal processing, one example of the use of band-pass filters is in the atmospheric sciences. It is common to band-pass filter recent meteorological data with a period range of, for example, 3 to 10 days, so that only cyclones remain as fluctuations in the data fields.

In neuroscience, visual cortical simple cells were first shown by David Hubel and Torsten Wiesel to have response properties that resemble Gabor filters, which are band-pass.[3]

4.6.4 See also

- Atomic line filter
- Audio crossover
- Band-stop filter

4.6.5 References

[1] E. R. Kanasewich (1981). *Time Sequence Analysis in Geophysics*. University of Alberta. p. 260. ISBN 0-88864-074-9.

[2] Belle A. Shenoi (2006). *Introduction to digital signal processing and filter design*. John Wiley and Sons. p. 120. ISBN 978-0-471-46482-2.

[3] Norman Stuart Sutherland (1979). *Tutorial Essays in Psychology*. Lawrence Erlbaum Associates. p. 68. ISBN 0-470-26652-X.

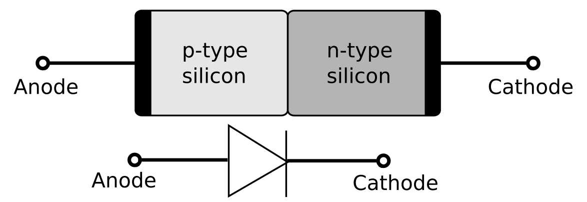
4.6.6 External links

Media related to Bandpass filters at Wikimedia Commons

Chapter 5

Basic devices

5.1 p–n junction



A p–n junction. The circuit symbol is shown: the triangle corresponds to the p side.

See also: p–n diode and Diode § Semiconductor diodes

A **p–n junction** is a boundary or interface between two types of semiconductor material, p-type and n-type, inside a single crystal of semiconductor. It is created by doping, for example by ion implantation, diffusion of dopants, or by epitaxy (growing a layer of crystal doped with one type of dopant on top of a layer of crystal doped with another type of dopant). If two separate pieces of material were used, this would introduce a grain boundary between the semiconductors that would severely inhibit its utility by scattering the electrons and holes.

p–n junctions are elementary "building blocks" of most semiconductor electronic devices such as diodes, transistors, solar cells, LEDs, and integrated circuits; they are the active sites where the electronic action of the device takes place. For example, a common type of transistor, the bipolar junction transistor, consists of two p–n junctions in series, in the form n–p–n or p–n–p.

The discovery of the p–n junction is usually attributed to American physicist Russell Ohl of Bell Laboratories.[1] However, Vadim Lashkaryov reported discovery of *p-n*-junctions in Cu_2O and silver sulphide photocells and selenium rectifiers in 1941.

A Schottky junction is a special case of a p–n junction, where metal serves the role of the p-type semiconductor.

5.1.1 Properties

The p–n junction possesses some interesting properties that have useful applications in modern electronics. A p-

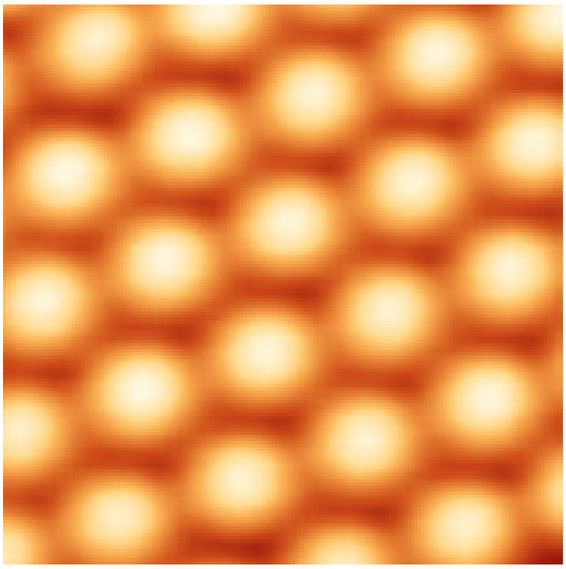


Image silicon atoms (Si) enlarged about 45,000,000x.

doped semiconductor is relatively conductive. The same is true of an n-doped semiconductor, but the junction between them can become depleted of charge carriers, and hence non-conductive, depending on the relative voltages of the two semiconductor regions. By manipulating this non-conductive layer, p–n junctions are commonly used as diodes: circuit elements that allow a flow of electricity in one direction but not in the other (opposite) direction. *Bias* is the application of a voltage across a p–n junction; *forward bias* is in the direction of easy current flow, and *reverse bias* is in the direction of little or no current flow.

Equilibrium (zero bias)

In a p–n junction, without an external applied voltage, an equilibrium condition is reached in which a potential difference is formed across the junction. This potential difference is called built-in potential V_{bi} .

After joining p-type and n-type semiconductors, electrons from the n region near the p–n interface tend to diffuse into the p region leaving behind positively charged ions in the n region and being recombined with holes, forming negatively charged ions in the p region. Likewise, holes from the p-type region near the p–n interface begin to diffuse into the n-type region, leaving behind negatively charged ions in the p region and recombining with electrons, forming positive ions in the n region. The regions near the p–n interface lose their neutrality and most of their mobile carriers, forming the space charge region or depletion layer (see figure A).

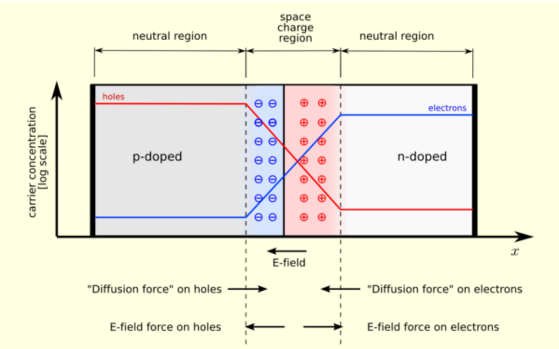


Figure A. *A p–n junction in thermal equilibrium with zero-bias voltage applied. Electron and hole concentration are reported with blue and red lines, respectively. Gray regions are charge-neutral. Light-red zone is positively charged. Light-blue zone is negatively charged. The electric field is shown on the bottom, the electrostatic force on electrons and holes and the direction in which the diffusion tends to move electrons and holes. (The log concentration curves should actually be smoother with slope varying with field strength.)*

The electric field created by the space charge region opposes the diffusion process for both electrons and holes. There are two concurrent phenomena: the diffusion process that tends to generate more space charge, and the electric field generated by the space charge that tends to counteract the diffusion. The carrier concentration profile at equilibrium is shown in figure A with blue and red lines. Also shown are the two counterbalancing phenomena that establish equilibrium.

The space charge region is a zone with a net charge provided by the fixed ions (donors or acceptors) that have been left *uncovered* by majority carrier diffusion. When equilibrium is reached, the charge density is approximated by the displayed step function. In fact, since the y-axis of figure A is log-scale, the region is almost completely depleted of majority carriers (leaving a charge density equal to the net doping level), and the edge between the space charge region and the neutral region is quite sharp (see figure B, Q(x) graph). The space charge region has the same magnitude of charge on both sides of the p–n interfaces, thus it extends farther on the less doped side in this example (the n side in figures A and B).

Forward bias

In forward bias, the p-type is connected with the positive terminal and the n-type is connected with the negative

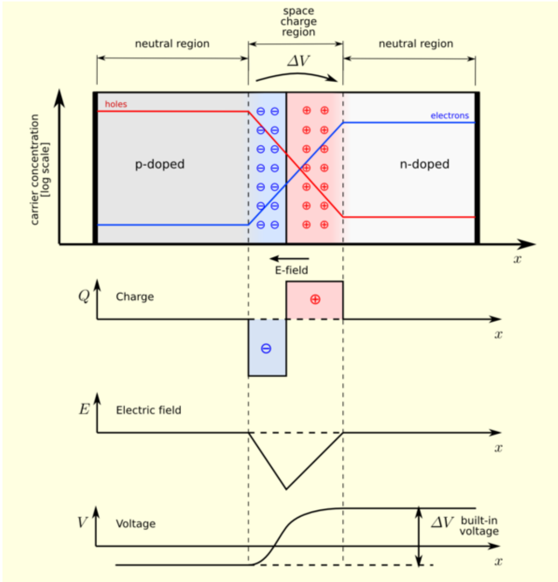
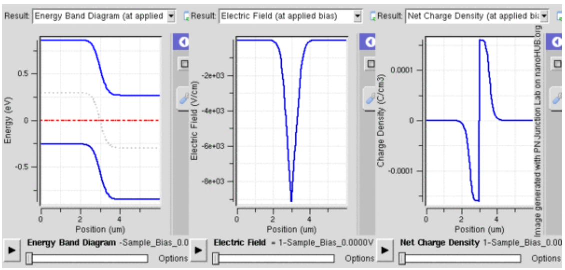


Figure B. *A p–n junction in thermal equilibrium with zero-bias voltage applied. Under the junction, plots for the charge density, the electric field, and the voltage are reported. (The log concentration curves should actually be smoother, like the voltage.)*

terminal.



PN junction operation in forward-bias mode, showing reducing depletion width. The panels show energy band diagram, electric field, and net charge density. Both p and n junctions are doped at a 1e15/cm3 (0.00016C/cm^3*) doping level, leading to built-in potential of ~0.59 V. Reducing depletion width can be inferred from the shrinking charge profile, as fewer dopants are exposed with increasing forward bias.*

With a battery connected this way, the holes in the p-type region and the electrons in the n-type region are pushed toward the junction and start to neutralize the depletion zone, reducing its width. The positive potential applied to the p-type material repels the holes, while the negative potential applied to the n-type material repels the electrons. The change in potential between the p side and the n side decreases or switches sign. With increasing forward-bias voltage, the depletion zone eventually becomes thin enough that the zone's electric field cannot counteract charge carrier motion across the p–n junction, which as a consequence reduces electrical resistance. The electrons that cross the p–n junction into the p-type material (or holes that cross into the n-type material) will diffuse into the nearby neutral region. The amount of minority diffusion in the near-neutral zones determines the amount of current that may flow through the diode.

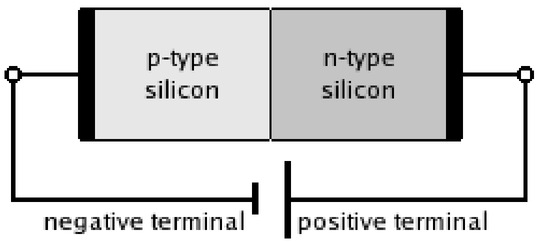
Only majority carriers (electrons in n-type material or holes in p-type) can flow through a semiconductor for a macroscopic length. With this in mind, consider the flow of electrons across the junction. The forward bias causes a force on the electrons pushing them from the N side toward the P side. With forward bias, the depletion region is narrow enough that electrons can cross the junction and *inject* into the p-type material. However, they do not continue to flow through the p-type material indefinitely, because it is energetically favorable for them to recombine with holes. The average length an electron travels through the p-type material before recombining is called the *diffusion length*, and it is typically on the order of micrometers.[2]

Although the electrons penetrate only a short distance into the p-type material, the electric current continues uninterrupted, because holes (the majority carriers) begin to flow in the opposite direction. The total current (the sum of the electron and hole currents) is constant in space, because any variation would cause charge buildup over time (this is Kirchhoff's current law). The flow of holes from the p-type region into the n-type region is exactly analogous to the flow of electrons from N to P (electrons and holes swap roles and the signs of all currents and voltages are reversed).

Therefore, the macroscopic picture of the current flow through the diode involves electrons flowing through the n-type region toward the junction, holes flowing through the p-type region in the opposite direction toward the junction, and the two species of carriers constantly recombining in the vicinity of the junction. The electrons and holes travel in opposite directions, but they also have opposite charges, so the overall current is in the same direction on both sides of the diode, as required.

The Shockley diode equation models the forward-bias operational characteristics of a p–n junction outside the avalanche (reverse-biased conducting) region.

Reverse bias



A silicon p–n junction in reverse bias.

Connecting the *p-type* region to the *negative* terminal of the battery and the *n-type* region to the *positive* terminal corresponds to reverse bias. If a diode is reverse-biased, the voltage at the cathode is comparatively higher than at the anode. Therefore, very little current will flow until the diode breaks down. The connections are illustrated in the diagram to the right.

Because the p-type material is now connected to the negative terminal of the power supply, the 'holes' in the p-type material are pulled away from the junction, leaving behind charged ions and causing the width of the depletion region to increase. Likewise, because the n-type region is connected to the positive terminal, the electrons will also be pulled away from the junction, with similar effect. This increases the voltage barrier causing a high resistance to the flow of charge carriers, thus allowing minimal electric current to cross the p–n junction. The increase in resistance of the p–n junction results in the junction behaving as an insulator.

The strength of the depletion zone electric field increases as the reverse-bias voltage increases. Once the electric field intensity increases beyond a critical level, the p–n junction depletion zone breaks down and current begins to flow, usually by either the Zener or the avalanche breakdown processes. Both of these breakdown processes are non-destructive and are reversible, as long as the amount of current flowing does not reach levels that cause the semiconductor material to overheat and cause thermal damage.

This effect is used to advantage in Zener diode regulator circuits. Zener diodes have a low breakdown voltage. A standard value for breakdown voltage is for instance 5.6 V. This means that the voltage at the cathode cannot be more than about 5.6 V higher than the voltage at the anode (although there is a slight rise with current), because the diode will break down – and therefore conduct – if the voltage gets any higher. This in effect limits the voltage over the diode.

Another application of reverse biasing is Varicap diodes, where the width of the depletion zone (controlled with the reverse bias voltage) changes the capacitance of the diode.

5.1.2 Governing equations

Size of depletion region

See also: Band bending

For a p–n junction, letting $C_A(x)$ and $C_D(x)$ be the concentrations of acceptor and donor atoms respectively, and letting $N_0(x)$ and $P_0(x)$ be the equilibrium concentrations of electrons and holes respectively, yields, by Poisson's equation:

$$-\frac{\mathrm{d}^2 V}{\mathrm{d}x^2} = \frac{\rho}{\varepsilon} = \frac{q}{\varepsilon}\left[(N_0 - P_0) + (C_D - C_A)\right]$$

where V is the electric potential, ρ is the charge density,

ε is permittivity and q is the magnitude of the electron charge. Letting d_p be the width of the depletion region within the p-side, and letting d_n be the width of the depletion region within the n-side, it must be that

$$d_p C_A = d_n C_D$$

because the total charge on either side of the depletion region must cancel out. Therefore, letting D and ΔV represent the entire depletion region and the potential difference across it,

$$\Delta V = \int_D \int \frac{q}{\varepsilon}\left[(N_0 - P_0) + (C_D - C_A)\right] \mathrm{d}x\,\mathrm{d}x$$
$$= \frac{C_A C_D}{C_A + C_D}\frac{2q}{\varepsilon}(d_p + d_n)^2$$

where $P_0 = N_0 = 0$, because we are in the depletion region. And thus, letting d be the total width of the depletion region, we get

$$d = \sqrt{\frac{2\varepsilon}{q}\frac{C_A + C_D}{C_A C_D}\Delta V}$$

ΔV can be written as $\Delta V_0 + \Delta V_{\text{ext}}$, where we have broken up the voltage difference into the equilibrium plus external components. The equilibrium potential results from diffusion forces, and thus we can calculate ΔV_0 by implementing the Einstein relation and assuming the semiconductor is nondegenerate (i.e. the product $P_0 N_0$ is independent of the Fermi energy):

$$\Delta V_0 = \frac{kT}{q} \ln\left(\frac{C_A C_D}{P_0 N_0}\right)$$

where T is the temperature of the semiconductor and k is Boltzmann constant.[3]

Current across depletion region

The *Shockley ideal diode equation* characterizes the current across a p–n junction as a function of external voltage and ambient conditions (temperature, choice of semiconductor, etc.). To see how it can be derived, we must examine the various reasons for current. The convention is that the forward (+) direction be pointed against the diode's built-in potential gradient at equilibrium.

- Forward Current ($\mathbf{J}_F$)
  - Diffusion Current: current due to local imbalances in carrier concentration n , via the equation $\mathbf{J}_D \propto -q\nabla n$
- Reverse Current ($\mathbf{J}_R$)
  - Field Current
  - Generation Current

5.1.3 Summary

The forward-bias and the reverse-bias properties of the p–n junction imply that it can be used as a diode. A p–n junction diode allows electric charges to flow in one direction, but not in the opposite direction; negative charges (electrons) can easily flow through the junction from n to p but not from p to n, and the reverse is true for holes. When the p–n junction is forward-biased, electric charge flows freely due to reduced resistance of the p–n junction. When the p–n junction is reverse-biased, however, the junction barrier (and therefore resistance) becomes greater and charge flow is minimal.

5.1.4 Non-rectifying junctions

In the above diagrams, contact between the metal wires and the semiconductor material also creates metal–semiconductor junctions called Schottky diodes. In a simplified ideal situation a semiconductor diode would never function, since it would be composed of several diodes connected back-to-front in series. But, in practice, surface impurities within the part of the semiconductor that touches the metal terminals will greatly reduce the width of those depletion layers to such an extent that the metal-semiconductor junctions do not act as diodes. These *non-rectifying junctions* behave as ohmic contacts regardless of applied voltage polarity.

5.1.5 See also

- Alloy-junction transistor
- Capacitance–voltage profiling
- Deep-level transient spectroscopy
- Delocalized electron
- Diode modelling
- Field-effect transistor
- n–p–n transistor
- p–n–p transistor
- Semiconductor detector
- Semiconductor device
- Transistor–transistor logic

5.1.6 References

[1] Riordan, Michael; Lillian Hoddeson (1988). *Crystal fire: the invention of the transistor and the birth of the information age*. USA: W. W. Norton & Company. pp. 88–97. ISBN 0-393-31851-6.

[2] Hook, J. R.; H. E. Hall (2001). *Solid State Physics*. John Wiley & Sons. ISBN 0-471-92805-4.

[3] Luque, Antonio; Steven Hegedus (29 March 2011). *Handbook of Photovoltaic Science and Engineering*. John Wiley & Sons. ISBN 978-0-470-97612-8.

5.1.7 Further reading

- Shockley, William (1949). "The Theory of p-n Junctions in Semiconductors and p-n Junction Transistors". *Bell System Technical Journal* **28** (3): 435–489. doi:10.1002/j.1538-7305.1949.tb03645.x.

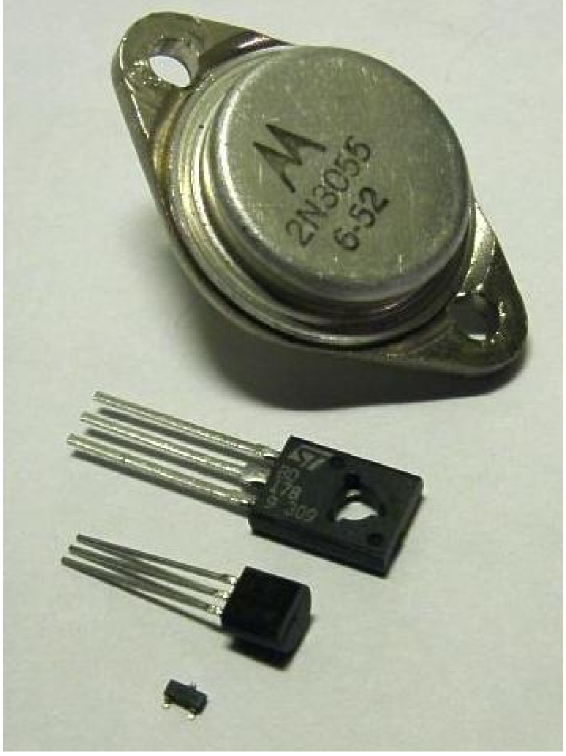
5.1.8 External links

- V. E. Lashkaryov, Investigation of a barrier layer by the thermoprobe method, Izv. Akad. Nauk SSSR, Ser. Fiz. **5**, 442-446 (1941), English translation: Ukr. J. Phys. **53**, 53-56 (2008),http://ujp.bitp.kiev.ua/files/journals/53/si/53SI11p.pdf. Report on discovery of *p*-*n*-junctions.
- http://www.youtube.com/watch?v=JBtEckh3L9Q Educational video on the P-N junction.
- "P-N Junction" – PowerGuru, August, 2012.
- Olav Torheim, *Elementary Physics of P-N Junctions*, 2007.
- PN Junction Properties Calculator
- PN Junction Lab free to use on nanoHUB.org allows simulation and study of a p–n junction diode with different doping and materials. Users can calculate current-voltage (I-V) & capacitance-voltage (C-V) outputs, as well.
- Understanding the PN Junction – Explains PN junction in a very easy to understand language.

5.2 Bipolar junction transistor

"Junction transistor" redirects here. For other uses, see Junction transistor (disambiguation).
"BJT" redirects here. For the Japanese language proficiency test, see Business Japanese Proficiency Test.
BJT schematic symbols
A **bipolar junction transistor** (**bipolar transistor** or **BJT**) is a type of transistor that uses both electron and hole charge carriers. In contrast, unipolar transistors, such as field-effect transistors, only use one kind of charge carrier. For their operation, BJTs use two junctions between two semiconductor types, n-type and p-type.

BJTs are manufactured in two types, NPN and PNP, and are available as individual components, or fabricated in integrated circuits, often in large numbers. The basic function of a BJT is to amplify current. This allows BJTs to be used as amplifiers or switches, giving them wide applicability in electronic equipment, including computers, televisions, mobile phones, audio amplifiers, industrial control, and radio transmitters.



Typical individual BJT packages. From top to bottom: TO-3, TO-126, TO-92, SOT-23

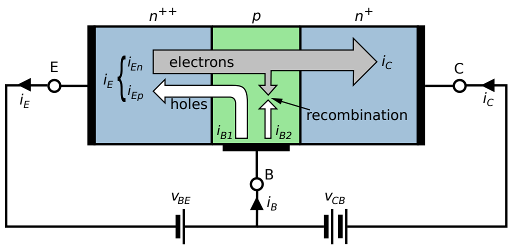
5.2.1 Note on current direction

By convention, the direction of current on diagrams is shown as the direction that a positive charge would move. This is called *conventional current*. However, current in metal conductors is due to the flow of electrons which, because they carry a negative charge, move in the opposite direction to conventional current. On the other hand, inside a bipolar transistor, currents can be composed of both positively charged holes and negatively charged electrons. In this article, current arrows are shown in the conventional direction, but labels for the movement of holes and electrons show their actual direction inside the transistor.

5.2.2 Function

BJTs come in two types, or polarities, known as PNP and NPN based on the doping types of the three main terminal regions. An NPN transistor comprises two semiconductor junctions that share a thin p-doped anode region, and a PNP transistor comprises two semiconductor junctions that share a thin n-doped cathode region.

Charge flow in a BJT is due to diffusion of charge carriers across a junction between two regions of different charge concentrations. The regions of a BJT are called *emitter*, *collector*, and *base*.[note 1] A discrete transistor has three leads for connection to these regions. Typically, the emitter region is heavily doped compared to the other



NPN BJT with forward-biased E–B junction and reverse-biased B–C junction

two layers, whereas the majority charge carrier concentrations in base and collector layers are about the same. By design, most of the BJT collector current is due to the flow of charges injected from a high-concentration emitter into the base where there are minority carriers that diffuse toward the collector, and so BJTs are classified as minority-carrier devices.

In typical operation, the base–emitter junction is forward biased, which means that the p-doped side of the junction is at a more positive potential than the n-doped side, and the base–collector junction is reverse biased. In an NPN transistor, when positive bias is applied to the base–emitter junction, the equilibrium is disturbed between the thermally generated carriers and the repelling electric field of the n-doped emitter depletion region. This allows thermally excited electrons to inject from the emitter into the base region. These electrons diffuse through the base from the region of high concentration near the emitter towards the region of low concentration near the collector. The electrons in the base are called *minority carriers* because the base is doped p-type, which makes holes the *majority carrier* in the base.

To minimize the percentage of carriers that recombine before reaching the collector–base junction, the transistor's base region must be thin enough that carriers can diffuse across it in much less time than the semiconductor's minority carrier lifetime. In particular, the thickness of the base must be much less than the diffusion length of the electrons. The collector–base junction is reverse-biased, and so little electron injection occurs from the collector to the base, but electrons that diffuse through the base towards the collector are swept into the collector by the electric field in the depletion region of the collector–base junction. The thin *shared* base and asymmetric collector–emitter doping are what differentiates a bipolar transistor from two *separate* and oppositely biased diodes connected in series.

Voltage, current, and charge control

The collector–emitter current can be viewed as being controlled by the base–emitter current (current control), or by the base–emitter voltage (voltage control). These views are related by the current–voltage relation of the base–emitter junction, which is just the usual exponential current–voltage curve of a p-n junction (diode).[1]

The physical explanation for collector current is the concentration of minority carriers in the base region.[1][2][3] Due to low level injection (in which there are much fewer excess carriers than normal majority carriers) the ambipolar transport rates (in which the excess majority and minority carriers flow at the same rate) is in effect determined by the excess minority carriers.

Detailed transistor models of transistor action, such as the Gummel–Poon model, account for the distribution of this charge explicitly to explain transistor behaviour more exactly.[4] The charge-control view easily handles phototransistors, where minority carriers in the base region are created by the absorption of photons, and handles the dynamics of turn-off, or recovery time, which depends on charge in the base region recombining. However, because base charge is not a signal that is visible at the terminals, the current- and voltage-control views are generally used in circuit design and analysis.

In analog circuit design, the current-control view is sometimes used because it is approximately linear. That is, the collector current is approximately β_F times the base current. Some basic circuits can be designed by assuming that the emitter–base voltage is approximately constant, and that collector current is beta times the base current. However, to accurately and reliably design production BJT circuits, the voltage-control (for example, Ebers–Moll) model is required.[1] The voltage-control model requires an exponential function to be taken into account, but when it is linearized such that the transistor can be modeled as a transconductance, as in the Ebers–Moll model, design for circuits such as differential amplifiers again becomes a mostly linear problem, so the voltage-control view is often preferred. For translinear circuits, in which the exponential I–V curve is key to the operation, the transistors are usually modeled as voltage-controlled current sources whose transconductance is proportional to their collector current. In general, transistor-level circuit design is performed using SPICE or a comparable analog circuit simulator, so model complexity is usually not of much concern to the designer.

Turn-on, turn-off, and storage delay

The bipolar transistor exhibits a few delay characteristics when turning on and off. Most transistors, and especially power transistors, exhibit long base-storage times that limit maximum frequency of operation in switching applications. One method for reducing this storage time is by using a Baker clamp.

Transistor parameters: alpha (α) and beta (β)

The proportion of electrons able to cross the base and reach the collector is a measure of the BJT efficiency.

The heavy doping of the emitter region and light doping of the base region causes many more electrons to be injected from the emitter into the base than holes to be injected from the base into the emitter.

The *common-emitter current gain* is represented by βF or the h-parameter hFE; it is approximately the ratio of the DC collector current to the DC base current in forward-active region. It is typically greater than 50 for small-signal transistors but can be smaller in transistors designed for high-power applications.

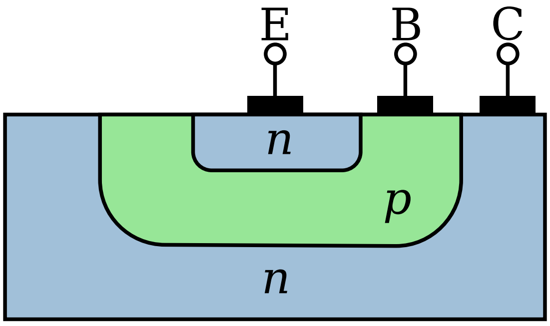
Another important parameter is the *common-base current gain*, αF. The common-base current gain is approximately the gain of current from emitter to collector in the forward-active region. This ratio usually has a value close to unity; between 0.980 and 0.998. It is less than unity due to recombination of charge carriers as they cross the base region.

Alpha and beta are more precisely related by the following identities (NPN transistor):

$$\alpha_F = \frac{I_{\mathrm{C}}}{I_{\mathrm{E}}}, \qquad \beta_F = \frac{I_{\mathrm{C}}}{I_{\mathrm{B}}}$$

$$\alpha_F = \frac{\beta_F}{1+\beta_F} \iff \beta_F = \frac{\alpha_F}{1-\alpha_F}$$

5.2.3 Structure

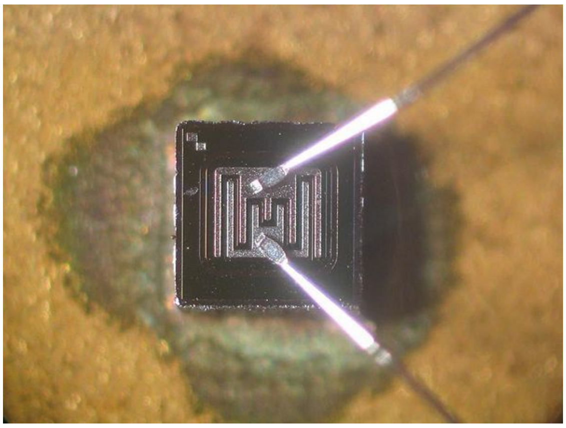


Simplified cross section of a planar NPN *bipolar junction transistor*

A BJT consists of three differently doped semiconductor regions: the *emitter* region, the *base* region and the *collector* region. These regions are, respectively, *p* type, *n* type and *p* type in a PNP transistor, and *n* type, *p* type and *n* type in an NPN transistor. Each semiconductor region is connected to a terminal, appropriately labeled: *emitter* (E), *base* (B) and *collector* (C).

The *base* is physically located between the *emitter* and the *collector* and is made from lightly doped, high resistivity material. The collector surrounds the emitter region, making it almost impossible for the electrons injected into the base region to escape without being collected, thus making the resulting value of α very close to unity, and so, giving the transistor a large β. A cross section view of a BJT indicates that the collector–base junction has a much larger area than the emitter–base junction.

The bipolar junction transistor, unlike other transistors, is usually not a symmetrical device. This means that interchanging the collector and the emitter makes the transistor leave the forward active mode and start to operate in reverse mode. Because the transistor's internal structure is usually optimized for forward-mode operation, interchanging the collector and the emitter makes the values of α and β in reverse operation much smaller than those in forward operation; often the α of the reverse mode is lower than 0.5. The lack of symmetry is primarily due to the doping ratios of the emitter and the collector. The emitter is heavily doped, while the collector is lightly doped, allowing a large reverse bias voltage to be applied before the collector–base junction breaks down. The collector–base junction is reverse biased in normal operation. The reason the emitter is heavily doped is to increase the emitter injection efficiency: the ratio of carriers injected by the emitter to those injected by the base. For high current gain, most of the carriers injected into the emitter–base junction must come from the emitter.



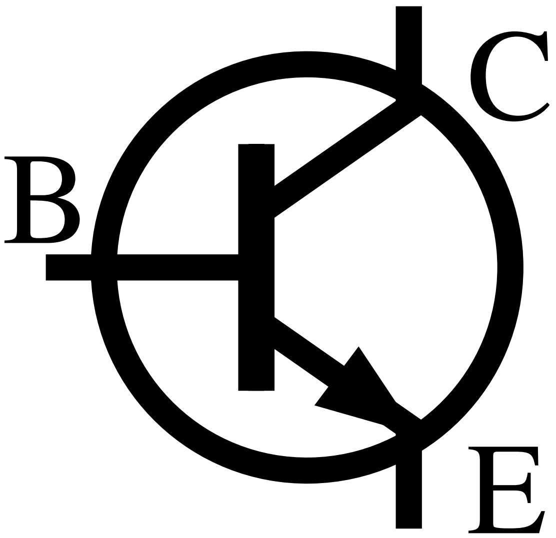
Die of a KSY34 high-frequency NPN transistor. Bond wires connect to the base and emitter

The low-performance "lateral" bipolar transistors sometimes used in CMOS processes are sometimes designed symmetrically, that is, with no difference between forward and backward operation.

Small changes in the voltage applied across the base–emitter terminals causes the current that flows between the *emitter* and the *collector* to change significantly. This effect can be used to amplify the input voltage or current. BJTs can be thought of as voltage-controlled current sources, but are more simply characterized as current-controlled current sources, or current amplifiers, due to the low impedance at the base.

Early transistors were made from germanium but most modern BJTs are made from silicon. A significant minority are also now made from gallium arsenide, especially for very high speed applications (see HBT, below).

NPN



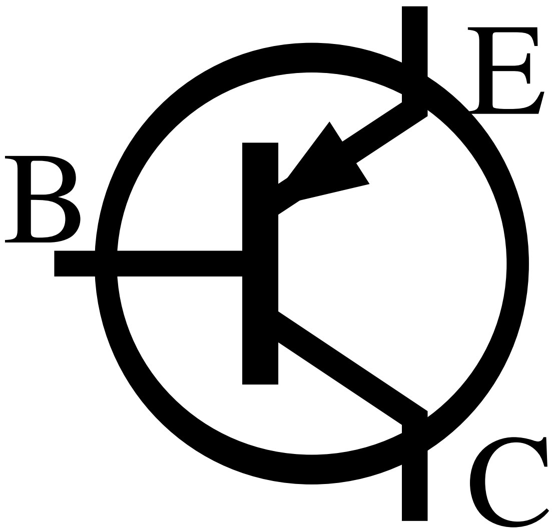
*The symbol of an NPN BJT. A mnemonic for the symbol is "**n**ot **p**ointing **in**."*

NPN is one of the two types of bipolar transistors, consisting of a layer of P-doped semiconductor (the "base") between two N-doped layers. A small current entering the base is amplified to produce a large collector and emitter current. That is, when there is a positive potential difference measured from the emitter of an NPN transistor to its base (i.e., when the base is **high** relative to the emitter) as well as positive potential difference measured from the base to the collector, the transistor becomes active. In this "on" state, current flows between the collector and emitter of the transistor. Most of the current is carried by electrons moving from emitter to collector as minority carriers in the P-type base region. To allow for greater current and faster operation, most bipolar transistors used today are NPN because electron mobility is higher than hole mobility.

A mnemonic device for the NPN transistor symbol is "*n*ot *p*ointing i*n*", based on the arrows in the symbol and the letters in the name.[5]

PNP

The other type of BJT is the PNP, consisting of a layer of N-doped semiconductor between two layers of P-doped material. A small current leaving the base is amplified in the collector output. That is, a PNP transistor is "on" when its base is pulled **low** relative to the emitter. In a PNP transistor, emitter-base region is forward biased. so electric field and carriers will be generated. They should flow towards the base junction, but the base part is very thin and has low conductivity. the reverse biased collector base part has generated holes. so due to the electric field, carriers or electrons get pulled by the holes.

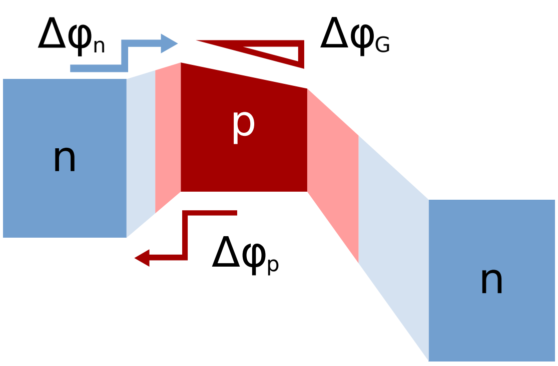


*The symbol of a PNP BJT. A mnemonic for the symbol is "**p**oints **in p**roudly."*

The arrows in the NPN and PNP transistor symbols are on the emitter legs and point in the direction of the conventional current flow when the device is in forward active mode.

A mnemonic device for the PNP transistor symbol is "*p*ointing i*n* (*p*roudly/*p*ermanently)", based on the arrows in the symbol and the letters in the name.[6]

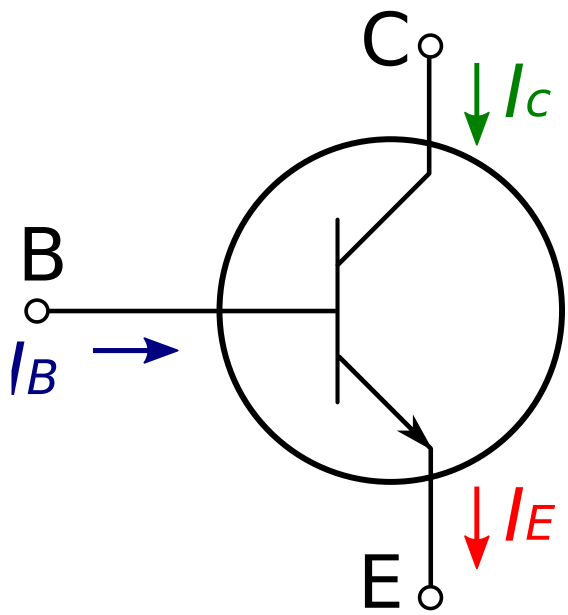
Heterojunction bipolar transistor



Bands in graded heterojunction NPN bipolar transistor. Barriers indicated for electrons to move from emitter to base, and for holes to be injected backward from base to emitter; Also, grading of bandgap in base assists electron transport in base region; Light colors indicate depleted regions

The heterojunction bipolar transistor (HBT) is an improvement of the BJT that can handle signals of very high frequencies up to several hundred GHz. It is common in modern ultrafast circuits, mostly RF systems.[7]

[8] Heterojunction transistors have different semiconductors for the elements of the transistor. Usually the emitter is composed of a larger bandgap material than the base.



Symbol for NPN Bipolar Transistor with current flow direction.

The figure shows that this difference in bandgap allows the barrier for holes to inject backward from the base into the emitter, denoted in the figure as $\Delta\varphi_p$, to be made large, while the barrier for electrons to inject into the base $\Delta\varphi_n$ is made low. This barrier arrangement helps reduce minority carrier injection from the base when the emitter-base junction is under forward bias, and thus reduces base current and increases emitter injection efficiency.

The improved injection of carriers into the base allows the base to have a higher doping level, resulting in lower resistance to access the base electrode. In the more traditional BJT, also referred to as homojunction BJT, the efficiency of carrier injection from the emitter to the base is primarily determined by the doping ratio between the emitter and base, which means the base must be lightly doped to obtain high injection efficiency, making its resistance relatively high. In addition, higher doping in the base can improve figures of merit like the Early voltage by lessening base narrowing.

The grading of composition in the base, for example, by progressively increasing the amount of germanium in a SiGe transistor, causes a gradient in bandgap in the neutral base, denoted in the figure by $\Delta\varphi G$, providing a “built-in” field that assists electron transport across the base. That drift component of transport aids the normal diffusive transport, increasing the frequency response of the transistor by shortening the transit time across the base.

Two commonly used HBTs are silicon–germanium and aluminum gallium arsenide, though a wide variety of semiconductors may be used for the HBT structure. HBT structures are usually grown by epitaxy techniques like MOCVD and MBE.

5.2.4 Regions of operation

Bipolar transistors have five distinct regions of operation, defined by BJT junction biases.

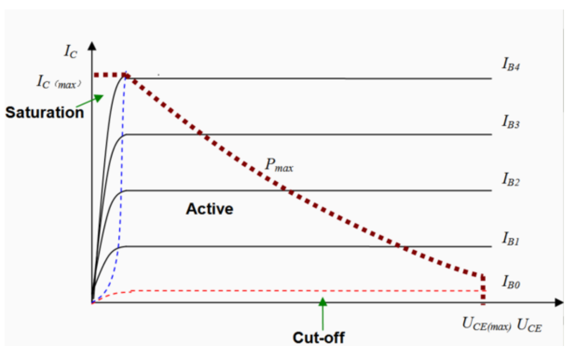
Forward-active (or simply, active) The base–emitter junction is forward biased and the base–collector junction is reverse biased. Most bipolar transistors are designed to afford the greatest common-emitter current gain, βF, in forward-active mode. If this is the case, the collector–emitter current is approximately proportional to the base current, but many times larger, for small base current variations.

Reverse-active (or inverse-active or inverted) By reversing the biasing conditions of the forward-active region, a bipolar transistor goes into reverse-active mode. In this mode, the emitter and collector regions switch roles. Because most BJTs are designed to maximize current gain in forward-active mode, the βF in inverted mode is several times smaller (2–3 times for the ordinary germanium transistor). This transistor mode is seldom used, usually being considered only for failsafe conditions and some types of bipolar logic. The reverse bias breakdown voltage to the base may be an order of magnitude lower in this region.

Saturation With both junctions forward-biased, a BJT is in saturation mode and facilitates high current conduction from the emitter to the collector (or the other direction in the case of NPN, with negatively charged carriers flowing from emitter to collector). This mode corresponds to a logical “on”, or a closed switch.

Cut-off In cut-off, biasing conditions opposite of saturation (both junctions reverse biased) are present. There is very little current, which corresponds to a logical “off”, or an open switch.

Avalanche breakdown region



The relationship between I_C, U_{CE} and I_B.

The modes of operation can be described in terms of the applied voltages (this description applies to NPN transistors; polarities are reversed for PNP transistors):

Forward-active Base higher than emitter, collector higher than base (in this mode the collector current is proportional to base current by β_F).

Saturation Base higher than emitter, but collector is not higher than base.

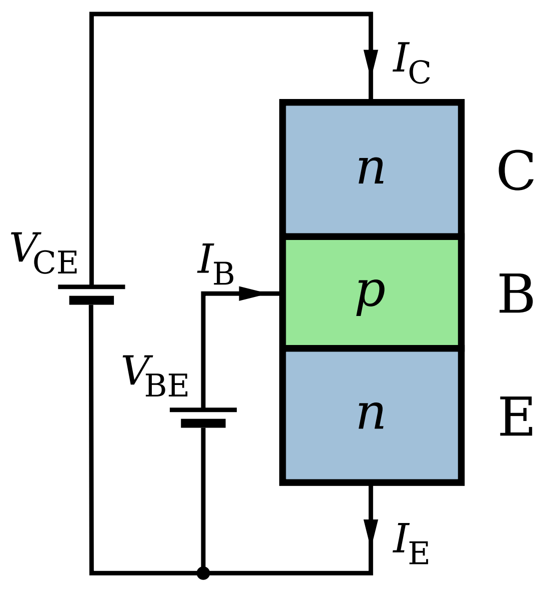
Cut-off Base lower than emitter, but collector is higher than base. It means the transistor is not letting conventional current go through from collector to emitter.

Reverse-active Base lower than emitter, collector lower than base: reverse conventional current goes through transistor.

In terms of junction biasing: (*reverse biased base–collector junction* means $V_{bc} < 0$ for NPN, opposite for PNP)

Although these regions are well defined for sufficiently large applied voltage, they overlap somewhat for small (less than a few hundred millivolts) biases. For example, in the typical grounded-emitter configuration of an NPN BJT used as a pulldown switch in digital logic, the “off” state never involves a reverse-biased junction because the base voltage never goes below ground; nevertheless the forward bias is close enough to zero that essentially no current flows, so this end of the forward active region can be regarded as the cutoff region.

Active-mode NPN transistors in circuits



Structure and use of NPN transistor. Arrow according to schematic.

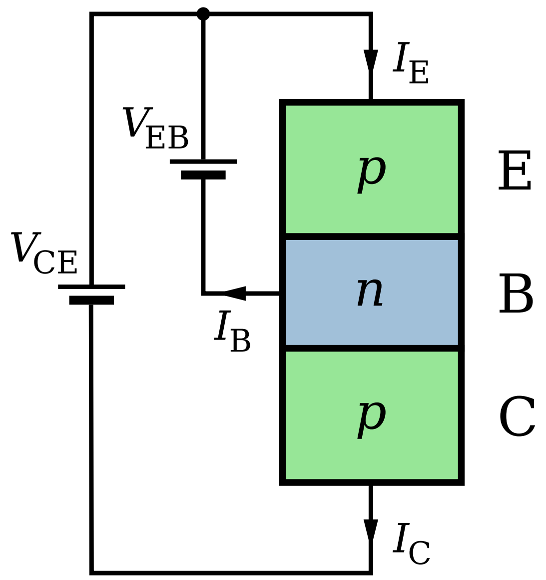
The diagram shows a schematic representation of an NPN transistor connected to two voltage sources. To make the transistor conduct appreciable current (on the order of 1 mA) from C to E, *V*BE must be above a minimum value sometimes referred to as the **cut-in voltage**. The cut-in voltage is usually about 650 mV for silicon BJTs at room temperature but can be different depending on the type of transistor and its biasing. This applied voltage causes the lower P-N junction to 'turn on', allowing a flow of electrons from the emitter into the base. In active mode, the electric field existing between base and collector (caused by *V*CE) will cause the majority of these electrons to cross the upper P-N junction into the collector to form the collector current *I*C. The remainder of the electrons recombine with holes, the majority carriers in the base, making a current through the base connection to form the base current, *I*B. As shown in the diagram, the emitter current, *I*E, is the total transistor current, which is the sum of the other terminal currents, (i.e., *I*E = *I*B + *I*C).

In the diagram, the arrows representing current point in the direction of conventional current – the flow of electrons is in the opposite direction of the arrows because electrons carry negative electric charge. In active mode, the ratio of the collector current to the base current is called the *DC current gain*. This gain is usually 100 or more, but robust circuit designs do not depend on the exact value (for example see op-amp). The value of this gain for DC signals is referred to as h_{FE} , and the value of this gain for small signals is referred to as h_{fe} . That is, when a small change in the currents occurs, and sufficient time has passed for the new condition to reach a steady state h_{fe} is the ratio of the change in collector current to the change in base current. The symbol β is used for both h_{FE} and h_{fe} .[9]

The emitter current is related to V_{BE} exponentially. At room temperature, an increase in V_{BE} by approximately 60 mV increases the emitter current by a factor of 10. Because the base current is approximately proportional to the collector and emitter currents, they vary in the same way.

Active-mode PNP transistors in circuits

The diagram shows a schematic representation of a PNP transistor connected to two voltage sources. To make the transistor conduct appreciable current (on the order of 1 mA) from E to C, V_{EB} must be above a minimum value sometimes referred to as the **cut-in voltage**. The cut-in voltage is usually about 650 mV for silicon BJTs at room temperature but can be different depending on the type of transistor and its biasing. This applied voltage causes the upper P-N junction to 'turn-on' allowing a flow of holes from the emitter into the base. In active mode, the electric field existing between the emitter and the collector (caused by V_{CE}) causes the majority of these holes to cross the lower p-n junction into the collector to form the collector current I_{C} . The remainder of the holes recombine with electrons, the majority carriers in the base,



Structure and use of PNP transistor.

making a current through the base connection to form the base current, I_B . As shown in the diagram, the emitter current, I_E , is the total transistor current, which is the sum of the other terminal currents (i.e., $IE = IB + IC$).

In the diagram, the arrows representing current point in the direction of conventional current – the flow of holes is in the same direction of the arrows because holes carry positive electric charge. In active mode, the ratio of the collector current to the base current is called the *DC current gain*. This gain is usually 100 or more, but robust circuit designs do not depend on the exact value. The value of this gain for DC signals is referred to as h_{FE} , and the value of this gain for AC signals is referred to as h_{fe} . However, when there is no particular frequency range of interest, the symbol β is used.

It should also be noted that the emitter current is related to V_{EB} exponentially. At room temperature, an increase in V_{EB} by approximately 60 mV increases the emitter current by a factor of 10. Because the base current is approximately proportional to the collector and emitter currents, they vary in the same way.

5.2.5 History

The bipolar point-contact transistor was invented in December 1947 at the Bell Telephone Laboratories by John Bardeen and Walter Brattain under the direction of William Shockley. The junction version known as the bipolar junction transistor, invented by Shockley in 1948, enjoyed three decades as the device of choice in the design of discrete and integrated circuits. Nowadays, the use of the BJT has declined in favor of CMOS technology in the design of digital integrated circuits. The incidental low performance BJTs inherent in CMOS ICs, however, are often utilized as bandgap voltage reference, silicon bandgap temperature sensor and to handle electrostatic discharge.

Germanium transistors

The germanium transistor was more common in the 1950s and 1960s, and while it exhibits a lower "cut off" voltage, typically around 0.2 V, making it more suitable for some applications, it also has a greater tendency to exhibit thermal runaway.

Early manufacturing techniques

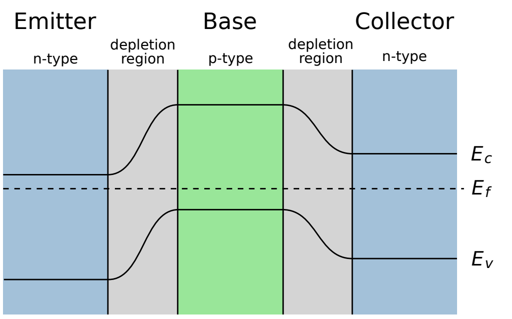
Various methods of manufacturing bipolar transistors were developed.[10]

Bipolar transistors

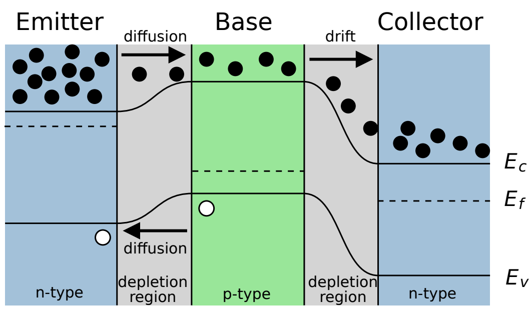
- Point-contact transistor – first transistor ever constructed (December 1947), a bipolar transistor, limited commercial use due to high cost and noise.
  - Tetrode point-contact transistor – Point-contact transistor having two emitters. It became obsolete in the middle 1950s.
- Junction transistors
  - Grown-junction transistor – first bipolar *junction* transistor made.[11] Invented by William Shockley at Bell Labs. Invented on June 23, 1948.[12] Patent filed on June 26, 1948.
  - Alloy-junction transistor – emitter and collector alloy beads fused to base. Developed at General Electric and RCA[13] in 1951.
    - Micro-alloy transistor (MAT) – high speed type of alloy junction transistor. Developed at Philco.[14]
    - Micro-alloy diffused transistor (MADT) – high speed type of alloy junction transistor, speedier than MAT, a diffused-base transistor. Developed at Philco.
    - Post-alloy diffused transistor (PADT) – high speed type of alloy junction transistor, speedier than MAT, a diffused-base transistor. Developed at Philips.
  - Tetrode transistor – high speed variant of grown-junction transistor[15] or alloy junction transistor[16] with two connections to base.
  - Surface-barrier transistor – high speed metal barrier junction transistor. Developed at Philco[17] in 1953.[18]

- Drift-field transistor – high speed bipolar junction transistor. Invented by Herbert Kroemer[19][20] at the Central Bureau of Telecommunications Technology of the German Postal Service, in 1953.
- Spacistor – circa 1957.
- Diffusion transistor – modern type bipolar junction transistor. Prototypes[21] developed at Bell Labs in 1954.
  - Diffused-base transistor – first implementation of diffusion transistor.
  - Mesa transistor – Developed at Texas Instruments in 1957.
  - Planar transistor – the bipolar junction transistor that made mass-produced monolithic integrated circuits possible. Developed by Dr. Jean Hoerni[22] at Fairchild in 1959.
- Epitaxial transistor – a bipolar junction transistor made using vapor phase deposition. See epitaxy. Allows very precise control of doping levels and gradients.

5.2.6 Theory and modeling



Band diagram for NPN transistor at equilibrium.



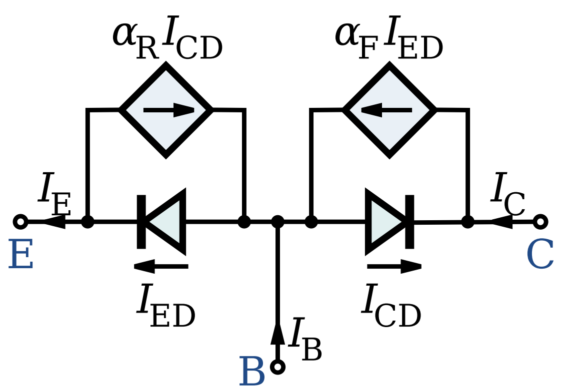
Band diagram for NPN transistor in active mode, showing injection of electrons from emitter to base, and their overshoot into the collector.

Transistors can be thought of as two diodes (P–N junctions) sharing a common region that minority carriers can move through. A PNP BJT will function like two diodes that share an N-type cathode region, and the NPN like two diodes sharing a P-type anode region. Connecting two diodes with wires will not make a transistor, since minority carriers will not be able to get from one P–N junction to the other through the wire.

Both types of BJT function by letting a small current input to the base control an amplified output from the collector. The result is that the transistor makes a good switch that is controlled by its base input. The BJT also makes a good amplifier, since it can multiply a weak input signal to about 100 times its original strength. Networks of transistors are used to make powerful amplifiers with many different applications. In the discussion below, focus is on the NPN bipolar transistor. In the NPN transistor in what is called active mode, the base–emitter voltage V_{BE} and collector–base voltage V_{CB} are positive, forward biasing the emitter–base junction and reverse-biasing the collector–base junction. In the active mode of operation, electrons are injected from the forward biased n-type emitter region into the p-type base where they diffuse as minority carriers to the reverse-biased n-type collector and are swept away by the electric field in the reverse-biased collector–base junction. For a figure describing forward and reverse bias, see semiconductor diodes.

Large-signal models

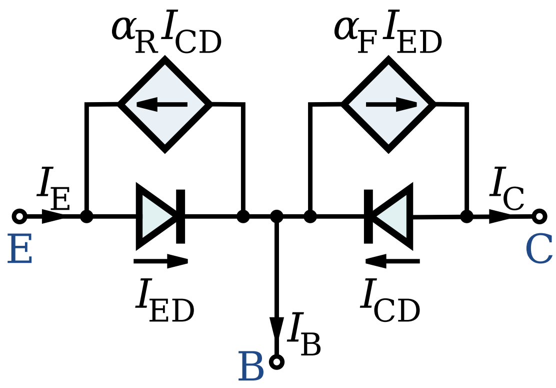
In 1954, Jewell James Ebers and John L. Moll introduced their mathematical model of transistor currents:[23]



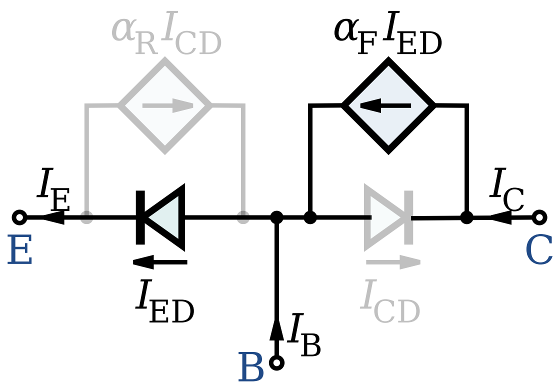
*Ebers–Moll Model for an NPN transistor.[24] * IB, IC, IE: base, collector and emitter currents * ICD, IED: collector and emitter diode currents * αF, αR: forward and reverse common-base current gains*

Ebers–Moll model The DC emitter and collector currents in active mode are well modeled by an approximation to the Ebers–Moll model:

$$I_E = I_{ES}\left(e^{\frac{V_{BE}}{V_T}} - 1\right)$$
$$I_C = \alpha_F I_E$$
$$I_B = (1 - \alpha_F)\, I_E$$



Ebers–Moll Model for a PNP transistor.



Approximated Ebers–Moll Model for an NPN transistor in the forward active mode. The collector diode is reverse-biased so ICD is virtually zero. Most of the emitter diode current (αF is nearly 1) is drawn from the collector, providing the amplification of the base current.

The base internal current is mainly by diffusion (see Fick's law) and

$$J_{n\,(\text{base})} = \frac{1}{W} q D_n n_{bo} e^{\frac{V_{EB}}{V_T}}$$

where

- V_T is the thermal voltage kT/q (approximately 26 mV at 300 K ≈ room temperature).
- I_E is the emitter current
- I_C is the collector current
- α_F is the common base forward short circuit current gain (0.98 to 0.998)
- I_{ES} is the reverse saturation current of the base–emitter diode (on the order of 10^{-15} to 10^{-12} amperes)
- V_{BE} is the base–emitter voltage
- D_n is the diffusion constant for electrons in the p-type base
- W is the base width

The α and forward β parameters are as described previously. A reverse β is sometimes included in the model.

The unapproximated Ebers–Moll equations used to describe the three currents in any operating region are given below. These equations are based on the transport model for a bipolar junction transistor.[25]

$$i_C = I_S\left[\left(e^{\frac{V_{BE}}{V_T}} - e^{\frac{V_{BC}}{V_T}}\right) - \frac{1}{\beta_R}\left(e^{\frac{V_{BC}}{V_T}} - 1\right)\right]$$

$$i_B = I_S\left[\frac{1}{\beta_F}\left(e^{\frac{V_{BE}}{V_T}} - 1\right) + \frac{1}{\beta_R}\left(e^{\frac{V_{BC}}{V_T}} - 1\right)\right]$$

$$i_E = I_S\left[\left(e^{\frac{V_{BE}}{V_T}} - e^{\frac{V_{BC}}{V_T}}\right) + \frac{1}{\beta_F}\left(e^{\frac{V_{BE}}{V_T}} - 1\right)\right]$$

where

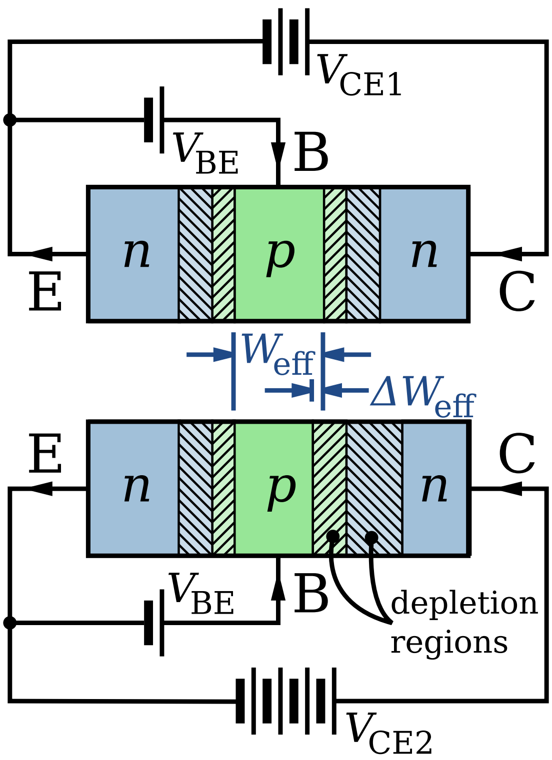
- i_C is the collector current
- i_B is the base current
- i_E is the emitter current
- β_F is the forward common emitter current gain (20 to 500)
- β_R is the reverse common emitter current gain (0 to 20)
- I_S is the reverse saturation current (on the order of 10^{-15} to 10^{-12} amperes)
- V_T is the thermal voltage (approximately 26 mV at 300 K ≈ room temperature).
- V_{BE} is the base–emitter voltage
- V_{BC} is the base–collector voltage

Base-width modulation Main article: Early Effect

As the collector–base voltage ($V_{CB} = V_{CE} - V_{BE}$) varies, the collector–base depletion region varies in size. An increase in the collector–base voltage, for example, causes a greater reverse bias across the collector–base junction, increasing the collector–base depletion region width, and decreasing the width of the base. This variation in base width often is called the "Early effect" after its discoverer James M. Early.

Narrowing of the base width has two consequences:

- There is a lesser chance for recombination within the "smaller" base region.
- The charge gradient is increased across the base, and consequently, the current of minority carriers injected across the emitter junction increases.



Top: NPN base width for low collector-base reverse bias; Bottom: narrower NPN base width for large collector-base reverse bias. Hashed regions are depleted regions.

Both factors increase the collector or "output" current of the transistor in response to an increase in the collector–base voltage.

In the forward-active region, the Early effect modifies the collector current (i_C) and the forward common emitter current gain (β_F) as given by:

$$i_C = I_S\, e^{\frac{v_{BE}}{V_T}} \left(1 + \frac{V_{CE}}{V_A}\right)$$

$$\beta_F = \beta_{F0} \left(1 + \frac{V_{CB}}{V_A}\right)$$

$$r_o = \frac{V_A}{I_C}$$

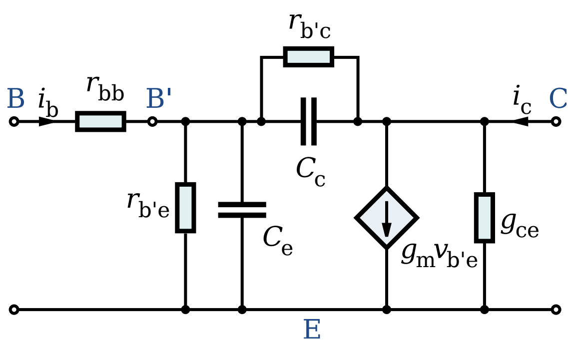
where:

- V_{CE} is the collector–emitter voltage
- V_A is the Early voltage (15 V to 150 V)
- β_{F0} is forward common-emitter current gain when V_{CB} = 0 V
- r_o is the output impedance
- I_C is the collector current

Punchthrough When the base–collector voltage reaches a certain (device specific) value, the base–collector depletion region boundary meets the base–emitter depletion region boundary. When in this state the transistor effectively has no base. The device thus loses all gain when in this state.

Gummel–Poon charge-control model The Gummel–Poon model[26] is a detailed charge-controlled model of BJT dynamics, which has been adopted and elaborated by others to explain transistor dynamics in greater detail than the terminal-based models typically do . This model also includes the dependence of transistor β -values upon the direct current levels in the transistor, which are assumed current-independent in the Ebers–Moll model.[27]

Small-signal models



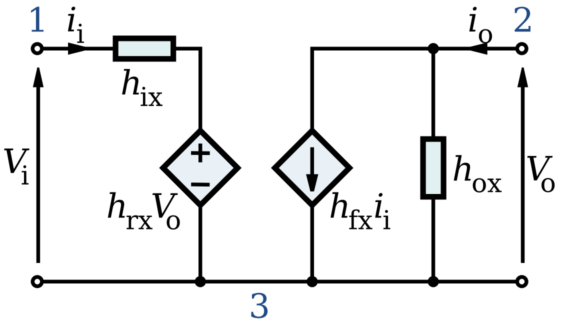
Hybrid-pi model

hybrid-pi model Main article: hybrid-pi model

The hybrid-pi model is a popular circuit model used for analyzing the small signal behavior of bipolar junction and field effect transistors. Sometimes it is also called *Giacoletto model* because it was introduced by L.J. Giacoletto in 1969. The model can be quite accurate for low-frequency circuits and can easily be adapted for higher frequency circuits with the addition of appropriate inter-electrode capacitances and other parasitic elements.

h-parameter model Another model commonly used to analyze BJT circuits is the *h-parameter* model, closely related to the hybrid-pi model and the y-parameter two-port, but using input current and output voltage as independent variables, rather than input and output voltages. This two-port network is particularly suited to BJTs as it lends itself easily to the analysis of circuit behaviour, and may be used to develop further accurate models. As shown, the term, *x*, in the model represents a different BJT lead depending on the topology used. For common-emitter mode the various symbols take on the specific values as:

- Terminal 1, base



Generalized h-parameter model of an NPN BJT.
Replace **x** with **e**, **b** or **c** for CE, CB and CC topologies respectively.

- Terminal 2, collector
- Terminal 3 (common), emitter; giving x to be e
- i_i, base current (i_b)
- i_o, collector current (i_c)
- V_{in}, base-to-emitter voltage (VBE)
- V_o, collector-to-emitter voltage (VCE)

and the h-parameters are given by:

- $h_{ix} = h_{ie}$, the input impedance of the transistor (corresponding to the base resistance r_{pi}).
- $h_{rx} = h_{re}$, represents the dependence of the transistor's IB–VBE curve on the value of VCE. It is usually very small and is often neglected (assumed to be zero).
- $h_{fx} = h_{fe}$, the current-gain of the transistor. This parameter is often specified as hFE or the DC current-gain (βDC) in datasheets.
- $h_{ox} = 1/h_{oe}$, the output impedance of transistor. The parameter h_{oe} usually corresponds to the output admittance of the bipolar transistor and has to be inverted to convert it to an impedance.

As shown, the h-parameters have lower-case subscripts and hence signify AC conditions or analyses. For DC conditions they are specified in upper-case. For the CE topology, an approximate h-parameter model is commonly used which further simplifies the circuit analysis. For this the h_{oe} and h_{re} parameters are neglected (that is, they are set to infinity and zero, respectively). It should also be noted that the h-parameter model as shown is suited to low-frequency, small-signal analysis. For high-frequency analyses the inter-electrode capacitances that are important at high frequencies must be added.

Etymology of hFE The 'h' refers to its being an h-parameter, a set of parameters named for their origin in a *hybrid equivalent circuit* model. 'F' is from *forward current amplification* also called the current gain. 'E' refers to the transistor operating in a *common emitter* (CE) configuration. Capital letters used in the subscript indicate that hFE refers to a direct current circuit.

Industry models

The Gummel Poon SPICE model is often used, but it suffers from several limitations. These have been addressed in various more advanced models: Mextram, VBIC, HICUM, Modella.[28][29][30][31]

5.2.7 Applications

The BJT remains a device that excels in some applications, such as discrete circuit design, due to the very wide selection of BJT types available, and because of its high transconductance and output resistance compared to MOSFETs.

The BJT is also the choice for demanding analog circuits, especially for very-high-frequency applications, such as radio-frequency circuits for wireless systems.

High speed digital logic

Emitter-coupled logic (ECL) use BJTs.

Bipolar transistors can be combined with MOSFETs in an integrated circuit by using a BiCMOS process of wafer fabrication to create circuits that take advantage of the application strengths of both types of transistor.

Amplifiers

Main article: Electronic amplifier

The transistor parameters α and β characterizes the current gain of the BJT. It is this gain that allow BJTs to be used as the building blocks of electronic amplifiers. The three main BJT amplifier topologies are :

- Common emitter
- Common base
- Common collector

Temperature sensors

Main article: Silicon bandgap temperature sensor

Because of the known temperature and current dependence of the forward-biased base–emitter junction voltage, the BJT can be used to measure temperature by subtracting two voltages at two different bias currents in a known ratio .

Logarithmic converters

Because base–emitter voltage varies as the log of the base–emitter and collector–emitter currents, a BJT can also be used to compute logarithms and anti-logarithms. A diode can also perform these nonlinear functions but the transistor provides more circuit flexibility.

5.2.8 Vulnerabilities

Exposure of the transistor to ionizing radiation causes radiation damage. Radiation causes a buildup of 'defects' in the base region that act as recombination centers. The resulting reduction in minority carrier lifetime causes gradual loss of gain of the transistor.

Power BJTs are subject to a failure mode called secondary breakdown, in which excessive current and normal imperfections in the silicon die cause portions of the silicon inside the device to become disproportionately hotter than the others. The doped silicon has a negative temperature coefficient, meaning that it conducts more current at higher temperatures. Thus, the hottest part of the die conducts the most current, causing its conductivity to increase, which then causes it to become progressively hotter again, until the device fails internally. The thermal runaway process associated with secondary breakdown, once triggered, occurs almost instantly and may catastrophically damage the transistor package.

If the emitter-base junction is reverse biased into avalanche or Zener mode and current flows for a short period of time, the current gain of the BJT will be permanently degraded.

5.2.9 See also

- Bipolar transistor biasing
- Gummel plot
- Technology CAD (TCAD)

5.2.10 Notes

[1] See point-contact transistor for the historical origin of these names.

5.2.11 References

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[15] Transistor Museum, Historic Transistor Photo Gallery, Western Electric 3N22

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[17] Transistor Museum, Historic Transistor Photo Gallery, Philco A01

[18] Transistor Museum, Historic Transistor Photo Gallery, Surface Barrier Transistor

[19] *Herb's Bipolar Transistors* IEEE Transactions on Electron Devices, vol. 48, no. 11, November 2001 PDF

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[22] Transistor Museum, Historic Transistor Photo Gallery, Fairchild 2N1613

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[29] Gennady Gildenblat, ed. (2010). *Compact Modeling: Principles, Techniques and Applications*. Springer Science & Business Media. Part II: Compact Models of Bipolar Junction Transistors, pp. 167-267 cover Mextram and HiCuM in-depth. ISBN 978-90-481-8614-3.

[30] Michael Schröter (2010). *Compact Hierarchical Bipolar Transistor Modeling with Hicum*. World Scientific. ISBN 978-981-4273-21-3.

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5.2.12 External links

- Simulation of a BJT in the Common Emitter Circuit
- Lessons In Electric Circuits – Bipolar Junction Transistors (Note: this site shows current as a flow of electrons, rather than the convention of showing it as a flow of holes)
- EncycloBEAMia – Bipolar Junction Transistor
- Characteristic curves
- ENGI 242/ELEC 222: BJT Small Signal Models
- Transistor Museum, Historic Transistor Timeline
- ECE 327: Transistor Basics – Summarizes simple Ebers–Moll model of a bipolar transistor and gives several common BJT circuits.
- ECE 327: Procedures for Output Filtering Lab – Section 4 ("Power Amplifier") discusses design of a BJT-Sziklai-pair-based class-AB current driver in detail.
- BJT Operation description for undergraduate and first year graduate students to describe the basic principles of operation of Bipolar Junction Transistor.

5.3 Amplifier

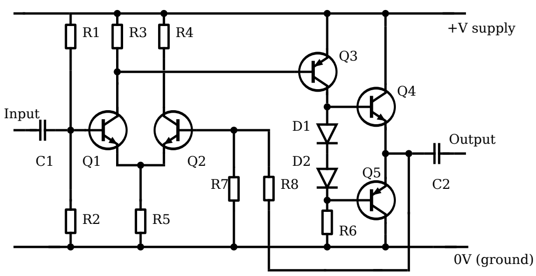
For other uses, see Amplifier (disambiguation).

An **amplifier**, **electronic amplifier** or (informally) **amp** is an electronic device that can increase the power of a signal.

It does this by taking energy from a power supply and controlling the output to match the input signal shape but with a larger amplitude. In this sense, an amplifier modulates the output of the power supply to make the output signal stronger than the input signal. An amplifier is effectively the opposite of an attenuator: while an amplifier provides gain, an attenuator provides loss.

An amplifier can either be a separate piece of equipment or an electrical circuit within another device. The ability to amplify is fundamental to modern electronics, and amplifiers are widely used in almost all electronic equipment. The types of amplifiers can be categorized in different ways. One is by the frequency of the electronic signal being amplified; audio amplifiers amplify signals in the audio (sound) range of less than 20 kHz, RF amplifiers amplify frequencies in the radio frequency range between 20 kHz and 300 GHz. Another is which quantity, voltage or current is being amplified; amplifiers can be divided into voltage amplifiers, current amplifiers, transconductance amplifiers, and transresistance amplifiers. A further distinction is whether the output is a linear or nonlinear representation of the input. Amplifiers can also be categorized by their physical placement in the signal chain.[1]

The first practical electronic device that could amplify was the Audion (triode) vacuum tube, invented in 1906 by Lee De Forest, which led to the first amplifiers. The terms "amplifier" and "amplification" (from the Latin *amplificare*, 'to enlarge or expand'[2]) were first used for this new capability around 1915 when triodes became widespread.[2] For the next 50 years, vacuum tubes were the only devices that could amplify. All amplifiers used them until the 1960s, when transistors appeared. Most amplifiers today use transistors, though tube amplifiers are still produced.



A practical bipolar transistor amplifier circuit

5.3.1 Figures of merit

Main article: Amplifier figures of merit

Amplifier quality is characterized by a list of specifications that include:

- **Gain**, the ratio between the magnitude of output and input signals
- **Bandwidth**, the width of the useful frequency range
- **Efficiency**, the ratio between the power of the output and total power consumption
- **Linearity**, the degree of proportionality between input and output
- **Noise**, a measure of undesired noise mixed into the output
- **Output dynamic range**, the ratio of the largest and the smallest useful output levels
- **Slew rate**, the maximum rate of change of the output
- **Rise time**, **settling time**, **ringing** and **overshoot** that characterize the step response
- **Stability**, the ability to avoid self-oscillation

5.3.2 Amplifier types

Amplifiers are described according to their input and output properties.[3] They exhibit the property of gain, or multiplication factor that relates the magnitude of the output signal to the input signal. The gain may be specified as the ratio of output voltage to input voltage (voltage gain), output power to input power (power gain), or some combination of current, voltage, and power. In many cases, with input and output in the same unit, gain is unitless (though often expressed in decibels (**dB**)).

The four basic types of amplifiers are as follows:[1]

1. Voltage amplifier – This is the most common type of amplifier. An input voltage is amplified to a larger output voltage. The amplifier's input impedance is high and the output impedance is low.

2. Current amplifier – This amplifier changes an input current to a larger output current. The amplifier's input impedance is low and the output impedance is high.

3. Transconductance amplifier – This amplifier responds to a changing input voltage by delivering a related changing output current.

4. Transresistance amplifier – This amplifier responds to a changing input current by delivering a related changing output voltage. Other names for the device are transimpedance amplifier and current-to-voltage converter.

In practice, amplifier power gain depends on the source and load impedances, as well as the inherent voltage and current gain. A radio frequency (RF) amplifier design typically optimizes impedances for power transfer, while audio and instrumentation amplifier designs normally optimize input and output impedance for least loading and highest signal integrity. An amplifier that is said to have a gain of 20 dB might have a voltage gain of ten times and an *available* power gain of much more than 20 dB (power ratio of 100)—yet actually deliver a much lower power gain if, for example, the input is from a 600 ohm microphone and the output connects to a 47 kilohm input socket for a power amplifier.

In most cases, an amplifier is linear. That is, it provides constant gain for any normal input level and output signal. If the gain is not linear, e.g., clipping of the signal, the output signal distorts. There are, however, cases where variable gain is useful. Certain signal processing applications use exponential gain amplifiers.[1]

Many different electronic amplifier types exist that are specific to areas such as: radio and television transmitters and receivers, high-fidelity ("hi-fi") stereo equipment, microcomputers and other digital equipment, and guitar and other instrument amplifiers. Essential components include active devices, such as vacuum tubes or transistors. A brief introduction to the many types of electronic amplifiers follows.

Power amplifier

The term *power amplifier* is a relative term with respect to the amount of power delivered to the load and/or provided by the power supply circuit. In general the power amplifier is the last 'amplifier' or actual circuit in a signal chain (the *output stage*) and is the amplifier stage that requires attention to power efficiency. Efficiency considerations lead to the various classes of power amplifier based on the biasing of the output transistors or tubes: see power amplifier classes.

Power amplifiers by application

- Audio power amplifiers: Speakers allow the client to use both sides to maximize volume, but each side receives half of what it could potentially supply.
- RF power amplifier—typical in transmitter final stages (see also: Linear amplifier)
- Servo motor controllers amplify a control voltage where linearity is not important
- Piezoelectric audio amplifier—includes a DC-to-DC converter to generate the high voltage output required to drive piezoelectric speakers[4]

Power amplifier circuits Power amplifier circuits include the following types:

- Vacuum tube/valve, hybrid or transistor power amplifiers
- Push-pull output or single-ended output stages

Vacuum-tube (valve) amplifiers

Main article: Valve amplifier

According to Symons, while semiconductor amplifiers have largely displaced valve amplifiers for low power applications, valve amplifiers are much more cost effective in high power applications such as "radar, countermeasures equipment, or communications equipment" (p. 56). Many microwave amplifiers are specially designed valves, such as the klystron, gyrotron, traveling wave tube, and crossed-field amplifier, and these microwave valves provide much greater single-device power output at microwave frequencies than solid-state devices (p. 59).[5]

Valves/tube amplifiers also have following uses in other areas, such as

- electric guitar amplification
- in Russian military aircraft, for their electromagnetic pulse (EMP) tolerance
- niche audio for their sound qualities (recording, and audiophile equipment)

Transistor amplifiers

See also: Transistor, Bipolar junction transistor, Field-effect transistor, JFET and MOSFET

An ECC83 tube glowing inside a preamp

The essential role of this active element is to magnify an input signal to yield a significantly larger output signal. The amount of magnification (the "forward gain") is determined by the external circuit design as well as the active device.

Many common active devices in transistor amplifiers are bipolar junction transistors (BJTs) and metal oxide semiconductor field-effect transistors (MOSFETs).

Applications are numerous, some common examples are audio amplifiers in a home stereo or PA system, RF high power generation for semiconductor equipment, to RF and Microwave applications such as radio transmitters.

Transistor-based amplifier can be realized using various configurations: for example with a bipolar junction transistor we can realize common base, common collector or common emitter amplifier; using a MOSFET we can realize common gate, common source or common drain amplifier. Each configuration has different characteristic (gain, impedance...).

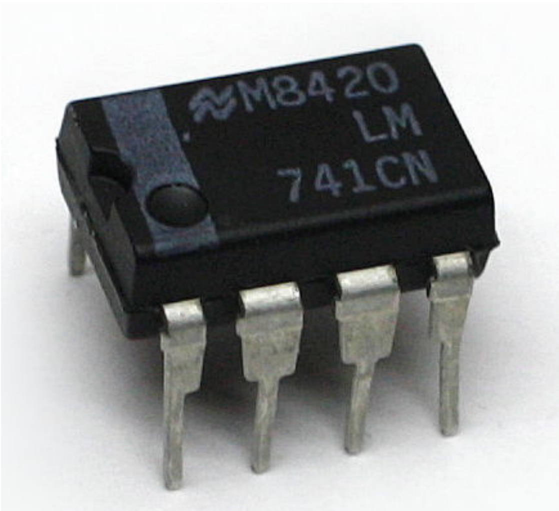
Magnetic amplifiers

Main article: Magnetic amplifier

These are devices somewhat similar to a transformer where one winding is used to control the saturation of a magnetic core and hence alter the impedance of the other winding.

They have largely fallen out of use due to development in semiconductor amplifiers but are still useful in HVDC control, and in nuclear power control circuitry to their not being affected by radioactivity.

Operational amplifiers (op-amps)



An LM741 general purpose op-amp

Main articles: Operational amplifier and Instrumentation amplifier

An operational amplifier is an amplifier circuit with very high open loop gain and differential inputs that employs external feedback to control its transfer function, or gain. Though the term today commonly applies to integrated circuits, the original operational amplifier design used valves, and later designs used discrete transistor circuits.

Fully differential amplifiers

Main article: Fully differential amplifier

A fully differential amplifier is a solid state integrated circuit amplifier that uses external feedback to control its transfer function or gain. It is similar to the operational amplifier, but also has differential output pins. These are usually constructed using BJTs or FETs.

Video amplifiers

These deal with video signals and have varying bandwidths depending on whether the video signal is for SDTV, EDTV, HDTV 720p or 1080i/p etc.. The specification of the bandwidth itself depends on what kind of filter is used—and at which point (-1 dB or -3 dB for example) the bandwidth is measured. Certain requirements for step response and overshoot are necessary for an acceptable TV image.

Oscilloscope vertical amplifiers

These deal with video signals that drive an oscilloscope display tube, and can have bandwidths of about 500 MHz. The specifications on step response, rise time, overshoot, and aberrations can make designing these amplifiers difficult. One of the pioneers in high bandwidth vertical amplifiers was the Tektronix company.

Distributed amplifiers

Main article: Distributed Amplifier

These use transmission lines to temporally split the signal and amplify each portion separately to achieve higher bandwidth than possible from a single amplifier. The outputs of each stage are combined in the output transmission line. This type of amplifier was commonly used on oscilloscopes as the final vertical amplifier. The transmission lines were often housed inside the display tube glass envelope.

Switched mode amplifiers

These nonlinear amplifiers have much higher efficiencies than linear amps, and are used where the power saving justifies the extra complexity.

Negative resistance devices

Negative resistances can be used as amplifiers, such as the tunnel diode amplifier.

Microwave amplifiers

Travelling wave tube amplifiers Main article: Traveling wave tube

Traveling wave tube amplifiers (TWTAs) are used for high power amplification at low microwave frequencies. They typically can amplify across a broad spectrum of frequencies; however, they are usually not as tunable as klystrons.

Klystrons Main article: Klystron

Klystrons are specialized linear-beam vacuum-devices, designed to provide high power, widely tunable amplification of millimetre and sub-millimetre waves. Klystrons are designed for large scale operations and despite having a narrower bandwidth than TWTAs, they have the advantage of coherently amplifying a reference signal so its output may be precisely controlled in amplitude, frequency and phase.

Musical instrument amplifiers

Main article: Instrument amplifier

An audio power amplifier is usually used to amplify signals such as music or speech. In the mid 1960s, amplifiers began to gain popularity because of its relatively low price ($50) and guitars being the most popular instruments as well.[6] Several factors are especially important in the selection of musical instrument amplifiers (such as guitar amplifiers) and other audio amplifiers (although the whole of the sound system – components such as microphones to loudspeakers – affect these parameters):

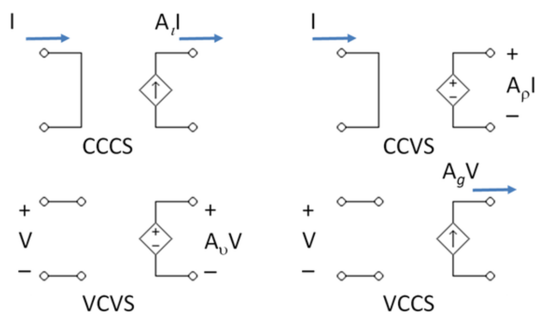
- Frequency response – not just the frequency range but the requirement that the signal level varies so little across the audible frequency range that the human ear notices no variation. A typical specification for audio amplifiers may be 20 Hz to 20 kHz +/- 0.5 dB.
- Power output – the power level obtainable with little distortion, to obtain a sufficiently loud sound pressure level from the loudspeakers.
- Low distortion – all amplifiers and transducers distort to some extent. They cannot be perfectly linear, but aim to pass signals without affecting the harmonic content of the sound more than the human ear can tolerate. That tolerance of distortion, and indeed the possibility that some “warmth” or second harmonic distortion (Tube sound) improves the “musicality” of the sound, are subjects of great debate.

Before coming onto the music scene, amplifiers were heavily used in cinema. In the premiere of Noah’s Ark in 1929, the movie’s director (Michael Kurtiz) used the amplifier for a festival following the movie’s premiere.[7]

5.3.3 Classification of amplifier stages and systems

Many alternative classifications address different aspects of amplifier designs, and they all express some particular perspective relating the design parameters to the objectives of the circuit. Amplifier design is always a compromise of numerous factors, such as cost, power consumption, real-world device imperfections, and a multitude of performance specifications. Below are several different approaches to classification:

Input and output variables



The four types of dependent source—control variable on left, output variable on right

Electronic amplifiers use one variable presented as either a current and voltage. Either current or voltage can be used as input and either as output, leading to four types of amplifiers. In idealized form they are represented by each of the four types of dependent source used in linear analysis, as shown in the figure, namely:

Each type of amplifier in its ideal form has an ideal input and output resistance that is the same as that of the corresponding dependent source:[8]

In practice the ideal impedances are only approximated. For any particular circuit, a small-signal analysis is often used to find the impedance actually achieved. A small-signal AC test current *Ix* is applied to the input or output node, all external sources are set to AC zero, and the corresponding alternating voltage *Vx* across the test current source determines the impedance seen at that node as $R = Vx / Ix$.

Amplifiers designed to attach to a transmission line at input and/or output, especially RF amplifiers, do not fit into this classification approach. Rather than dealing with voltage or current individually, they ideally couple with an input and/or output impedance matched to the transmission line impedance, that is, match *ratios* of voltage to current. Many real RF amplifiers come close to this ideal. Although, for a given appropriate source and load impedance, RF amplifiers can be characterized as amplifying voltage or current, they fundamentally are amplifying power.[9]

Common terminal

One set of classifications for amplifiers is based on which device terminal is common to both the input and the output circuit. In the case of bipolar junction transistors, the three classes are common emitter, common base, and common collector. For field-effect transistors, the corresponding configurations are common source, common gate, and common drain; for triode vacuum devices, *common cathode*, *common grid*, and *common plate*. The common emitter (or common source, common cathode, etc.) is most often configured to provide amplification of a voltage applied between base and emitter, and the output signal taken between collector and emitter is inverted, relative to the input. The common collector arrangement applies the input voltage between base and *collector*, and to take the output voltage between emitter and *collector*. This causes negative feedback, and the output voltage tends to 'follow' the input voltage. (This arrangement is also used as the input presents a high impedance and does not load the signal source, though the voltage amplification is less than 1 (unity).) The common-collector circuit is, therefore, better known as an *emitter follower*, *source follower*, *or cathode follower*,

Unilateral or bilateral

An amplifier whose output exhibits no feedback to its input side is described as 'unilateral'. The input impedance of a unilateral amplifier is independent of load, and output impedance is independent of signal source impedance.

An amplifier that uses feedback to connect part of the output back to the input is a *bilateral* amplifier. Bilateral amplifier input impedance depends on the load, and output impedance on the signal source impedance. All amplifiers are bilateral to some degree; however they may often be modeled as unilateral under operating conditions where feedback is small enough to neglect for most purposes, simplifying analysis (see the common base article for an example).

An amplifier design often deliberately applies negative feedback to tailor amplifier behavior. Some feedback, positive or negative, is unavoidable and often undesirable—introduced, for example, by parasitic elements, such as inherent capacitance between input and output of devices such as transistors, and capacitive coupling of external wiring. Excessive frequency-dependent positive feedback can turn an amplifier into an oscillator.

Linear unilateral and bilateral amplifiers can be represented as two-port networks.

Inverting or non-inverting

Another way to classify amplifiers is by the phase relationship of the input signal to the output signal. An 'inverting' amplifier produces an output 180 degrees out of phase with the input signal (that is, a polarity inversion or mirror image of the input as seen on an oscilloscope). A 'non-inverting' amplifier maintains the phase of the input signal waveforms. An emitter follower is a type of non-inverting amplifier, indicating that the signal at the emitter of a transistor is following (that is, matching with unity gain but perhaps an offset) the input signal. Voltage follower is also non inverting type of amplifier having unity gain.

This description can apply to a single stage of an amplifier, or to a complete amplifier system.

Function

Other amplifiers may be classified by their function or output characteristics. These functional descriptions usually apply to complete amplifier systems or sub-systems and rarely to individual stages.

- A **servo amplifier** indicates an integrated feedback loop to actively control the output at some desired level. A DC servo indicates use at frequencies down to DC levels, where the rapid fluctuations of an audio or RF signal do not occur. These are often used in mechanical actuators, or devices such as DC motors that must maintain a constant speed or torque. An **AC servo** amp can do this for some ac motors.

- A **linear** amplifier responds to different frequency components independently, and does not generate harmonic distortion or Intermodulation distortion. No amplifier can provide *perfect* linearity (even the most linear amplifier has some nonlinearities, since the amplifying devices—transistors or vacuum tubes—follow nonlinear power laws such as square-laws and rely on circuitry techniques to reduce those effects).

- A **nonlinear** amplifier generates significant distortion and so changes the harmonic content; there are situations where this is useful. Amplifier circuits intentionally providing a non-linear transfer function include:

  - a device like a Silicon Controlled Rectifier or a transistor used as a switch may be employed to turn either fully ON or OFF a load such as a lamp based on a threshold in a continuously variable input.

  - a non-linear amplifier in an analog computer or true RMS converter for example can provide a special transfer function, such as logarithmic or square-law.

  - a Class C RF amplifier may be chosen because it can be very efficient—but is non-linear. Following such an amplifier with a "tank" tuned circuit can reduce unwanted harmonics (distortion) sufficiently to make it useful in transmitters, or some desired harmonic may be selected by setting the resonant frequency of the tuned circuit to a higher frequency rather than fundamental frequency in frequency multiplier circuits.

- Automatic gain control circuits require an amplifier's gain be controlled by the time-averaged amplitude so that the output amplitude varies little when weak stations are being received. The non-linearities are assumed arranged so the relatively small signal amplitude suffers from little distortion (cross-channel interference or intermodulation) yet is still modulated by the relatively large gain-control DC voltage.
- AM detector circuits that use amplification such as Anode-bend detectors, Precision rectifiers and Infinite impedance detectors (so excluding *unamplified* detectors such as Cat's-whisker detectors), as well as peak detector circuits, rely on changes in amplification based on the signal's instantaneous amplitude to derive a direct current from an alternating current input.
- Operational amplifier comparator and detector circuits.

* A **wideband** amplifier has a precise amplification factor over a wide frequency range, and is often used to boost signals for relay in communications systems. A **narrowband** amp amplifies a specific narrow range of frequencies, to the exclusion of other frequencies.
* An **RF** amplifier amplifies signals in the radio frequency range of the electromagnetic spectrum, and is often used to increase the sensitivity of a receiver or the output power of a transmitter.[10]
* An **audio amplifier** amplifies audio frequencies. This category subdivides into small signal amplification, and power amps that are optimised to driving speakers, sometimes with multiple amps grouped together as separate or bridgeable channels to accommodate different audio reproduction requirements. Frequently used terms within audio amplifiers include:
  - Preamplifier (preamp), which may include a phono preamp with RIAA equalization, or tape head preamps with CCIR equalisation filters. They may include filters or tone control circuitry.
  - Power amplifier (normally drives loudspeakers), headphone amplifiers, and public address amplifiers.
  - Stereo amplifiers imply two channels of output (left and right), though the term simply means "solid" sound (referring to three-dimensional)—so quadraphonic stereo was used for amplifiers with four channels. 5.1 and 7.1 systems refer to Home theatre systems with 5 or 7 normal spacial channels, plus a subwoofer channel.
* Buffer amplifiers, which may include emitter followers, provide a high impedance input for a device (perhaps another amplifier, or perhaps an energy-hungry load such as lights) that would otherwise draw too much current from the source. Line drivers are a type of buffer that feeds long or interference-prone interconnect cables, possibly with differential outputs through twisted pair cables.
* A special type of amplifier - originally used in analog computers - is widely used in measuring instruments for signal processing, and many other uses. These are called **operational amplifiers** or **op-amps**. The "operational" name is because this type of amplifier can be used in circuits that perform mathematical algorithmic functions, or "operations" on input signals to obtain specific types of output signals. Modern op-amps are usually provided as integrated circuits, rather than constructed from discrete components. A typical modern op-amp has differential inputs (one "inverting", one "non-inverting") and one output. An *idealised* op-amp has the following characteristics:
  - Infinite input impedance (so it does not load the circuitry at its input)
  - Zero output impedance
  - Infinite gain
  - Zero propagation delay

The performance of an op-amp with these characteristics is entirely defined by the (usually passive) components that form a negative feedback loop around it. The amplifier itself does not affect the output. All real-world op-amps fall short of the idealised specification above—but some modern components have remarkable performance and come close in some respects.

Interstage coupling method

See also: multistage amplifiers

Amplifiers are sometimes classified by the coupling method of the signal at the input, output, or between stages. Different types of these include:

Resistive-capacitive (RC) coupled amplifier, using a network of resistors and capacitors
By design these amplifiers cannot amplify DC signals as the capacitors block the DC component of

the input signal. RC-coupled amplifiers were used very often in circuits with vacuum tubes or discrete transistors. In the days of the integrated circuit a few more transistors on a chip are much cheaper and smaller than a capacitor.

Inductive-capacitive (LC) coupled amplifier, using a network of inductors and capacitors
This kind of amplifier is most often used in selective radio-frequency circuits.

Transformer coupled amplifier, using a transformer to match impedances or to decouple parts of the circuits
Quite often LC-coupled and transformer-coupled amplifiers cannot be distinguished as a transformer is some kind of inductor.

Direct coupled amplifier, using no impedance and bias matching components
This class of amplifier was very uncommon in the vacuum tube days when the anode (output) voltage was at greater than several hundred volts and the grid (input) voltage at a few volts minus. So they were only used if the gain was specified down to DC (e.g., in an oscilloscope). In the context of modern electronics developers are encouraged to use directly coupled amplifiers whenever possible.

Frequency range

Depending on the frequency range and other properties amplifiers are designed according to different principles.

- Frequency ranges down to DC are only used when this property is needed. DC amplification leads to specific complications that are avoided if possible; **DC-blocking** capacitors can be added to remove DC and sub-sonic frequencies from audio amplifiers.

- Depending on the frequency range specified different design principles must be used. Up to the MHz range only "discrete" properties need be considered; e.g., a terminal has an input impedance.

- As soon as any connection within the circuit gets longer than perhaps 1% of the wavelength of the highest specified frequency (e.g., at 100 MHz the wavelength is 3 m, so the critical connection length is approx. 3 cm) design properties radically change. For example, a specified length and width of a PCB trace can be used as a selective or impedance-matching entity.

- Above a few hundred MHz, it gets difficult to use discrete elements, especially inductors. In most cases, PCB traces of very closely defined shapes are used instead.

The frequency range handled by an amplifier might be specified in terms of bandwidth (normally implying a response that is 3 dB down when the frequency reaches the specified bandwidth), or by specifying a **frequency response** that is within a certain number of decibels between a lower and an upper frequency (e.g. "20 Hz to 20 kHz plus or minus 1 dB").

5.3.4 Power amplifier classes

Power amplifier circuits (output stages) are classified as A, B, AB and C for analog designs—and class D and E for switching designs based on the proportion of each input cycle (conduction angle), during which an amplifying device passes current. The image of the conduction angle derives from amplifying a sinusoidal signal. If the device is always on, the conducting angle is 360°. If it is on for only half of each cycle, the angle is 180°. The angle of flow is closely related to the amplifier power efficiency. The various classes are introduced below, followed by a more detailed discussion under their individual headings further down.

In the illustrations below, a bipolar junction transistor is shown as the amplifying device. However the same attributes are found with MOSFETs or vacuum tubes.

Conduction angle classes

Class A 100% of the input signal is used (conduction angle $\Theta = 360°$). The active element remains conducting[11] all of the time.

Class B 50% of the input signal is used ($\Theta = 180°$); the active element carries current half of each cycle, and is turned off for the other half.

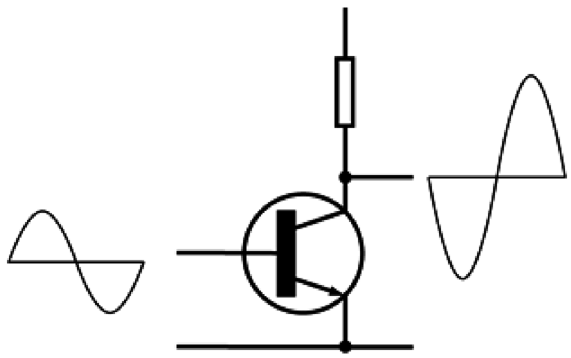
Class AB Class AB is intermediate between class A and B, the two active elements conduct more than half of the time

Class C Less than 50% of the input signal is used (conduction angle $\Theta < 180°$).

A "Class D" amplifier uses some form of pulse-width modulation to control the output devices; the conduction angle of each device is no longer related directly to the input signal but instead varies in pulse width. These are sometimes called "digital" amplifiers because the output device is switched fully on or off, and not carrying current proportional to the signal amplitude.

Additional classes There are several other amplifier classes, although they are mainly variations of the previous classes. For example, class-G and class-H amplifiers are marked by variation of the supply rails (in discrete steps or in a continuous fashion, respectively) following the input signal. Wasted heat on the output devices can be reduced as excess voltage is kept to a minimum. The amplifier that is fed with these rails itself can be of any class. These kinds of amplifiers are more complex, and are mainly used for specialized applications, such as very high-power units. Also, class-E and class-F amplifiers are commonly described in literature for radio-frequency applications where efficiency of the traditional classes is important, yet several aspects deviate substantially from their ideal values. These classes use harmonic tuning of their output networks to achieve higher efficiency and can be considered a subset of class C due to their conduction-angle characteristics.

Class A



Class-A amplifier

Amplifying devices operating in class A conduct over the entire range of the input cycle. A *class-A amplifier* is distinguished by the output stage devices being biased for class A operation. Subclass A2 is sometimes used to refer to vacuum-tube class-A stages that drive the grid slightly positive on signal peaks for slightly more power than normal class A (A1; where the grid is always negative[12]). This, however, incurs higher signal distortion.

Advantages of class-A amplifiers

- Class-A designs are simpler than other classes; for example class -AB and -B designs require two connected devices in the circuit (push–pull output), each to handle one half of the waveform; class A can use a single device (single-ended).
- The amplifying element is biased so the device is always conducting, the quiescent (small-signal) collector current (for transistors; drain current for FETs or anode/plate current for vacuum tubes) is close to the most linear portion of its transconductance curve.
- Because the device is never 'off' there is no "turn on" time, no problems with charge storage, and generally better high frequency performance and feedback loop stability (and usually fewer high-order harmonics).
- The point where the device comes closest to being 'off' is not at 'zero signal', so the problems of crossover distortion associated with class-AB and -B designs is avoided.
- Best for low signal levels of radio receivers due to low distortion.

Disadvantage of class-A amplifiers

- Class-A amplifiers are inefficient. A theoretical efficiency of 50% is obtainable in a push-pull topology, and only 25% in a single-ended topology, unless deliberate use of nonlinearities is made (such as in **square-law output stages**). In a power amplifier, this not only wastes power and limits operation with batteries, but increases operating costs and requires higher-rated output devices. Inefficiency comes from the standing current that must be roughly half the maximum output current, and a large part of the power supply voltage is present across the output device at low signal levels. If high output power is needed from a class-A circuit, the power supply and accompanying heat becomes significant. For every watt delivered to the load, the amplifier itself, at best, uses an extra watt. For high power amplifiers this means very large and expensive power supplies and heat sinks.

Class-A power amplifier designs have largely been superseded by more efficient designs, though they remain popular with some hobbyists, mostly for their simplicity. There is a market for expensive **high fidelity** class-A amps considered a "cult item" among audiophiles[13] mainly for their absence of crossover distortion and reduced odd-harmonic and high-order harmonic distortion.

Single-ended and triode class-A amplifiers Some hobbyists who prefer class-A amplifiers also prefer the use of thermionic valve (or "tube") designs instead of transistors, for several reasons:

- Single-ended output stages have an asymmetrical transfer function, meaning that even-order harmonics in the created distortion tend to not cancel out (as they do in push–pull output stages). For tubes, or FETs, most distortion is second-order harmonics, from the square law transfer characteristic, which to some produces a "warmer" and more pleasant sound.[14][15]
- For those who prefer low distortion figures, the use of tubes with class A (generating little odd-harmonic

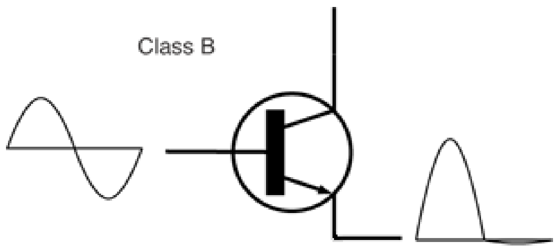
distortion, as mentioned above) together with symmetrical circuits (such as push–pull output stages, or balanced low-level stages) results in the cancellation of most of the even distortion harmonics, hence the removal of most of the distortion.

- Historically, valve amplifiers often used a class-A power amplifier simply because valves are large and expensive; many class-A designs use only a single device.

Transistors are much cheaper, and so more elaborate designs that give greater efficiency but use more parts are still cost-effective. A classic application for a pair of class-A devices is the long-tailed pair, which is exceptionally linear, and forms the basis of many more complex circuits, including many audio amplifiers and almost all op-amps.

Class-A amplifiers are often used in output stages of high quality op-amps (although the accuracy of the bias in low cost op-amps such as the **741** may result in class A or class AB or class B performance, varying from device to device or with temperature). They are sometimes used as medium-power, low-efficiency, and high-cost audio power amplifiers. The power consumption is unrelated to the output power. At idle (no input), the power consumption is essentially the same as at high output volume. The result is low efficiency and high heat dissipation.

Class B



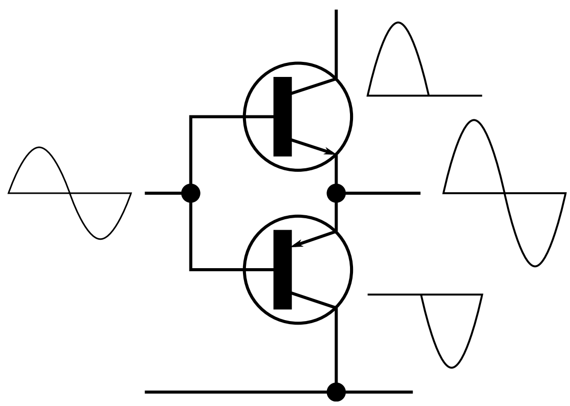
Class-B amplifier

Class-B amplifiers only amplify half of the input wave cycle, thus creating a large amount of distortion, but their efficiency is greatly improved and is much better than class A. Class-B amplifiers are also favoured in battery-operated devices, such as transistor radios. Class B has a maximum theoretical efficiency of $\pi/4$ ($\approx$ 78.5%). This is because the amplifying element is switched off altogether half of the time, and so cannot dissipate power. A single class-B element is rarely found in practice, though it has been used for driving the loudspeaker in the early IBM Personal Computers with beeps, and it can be used in RF power amplifier where the distortion levels are less important. However, class C is more commonly used for this.

A practical circuit using class-B elements is the push–pull stage, such as the very simplified complementary pair arrangement shown below. Here, complementary or quasi-complementary devices are each used for amplifying the opposite halves of the input signal, which is then recombined at the output. This arrangement gives excellent efficiency, but can suffer from the drawback that there is a small mismatch in the cross-over region – at the “joins” between the two halves of the signal, as one output device has to take over supplying power exactly as the other finishes. This is called crossover distortion. An improvement is to bias the devices so they are not completely off when they are not in use. This approach is called *class AB* operation.

Class B amplifiers offer higher efficiency than class A amplifier using a single active device.

Class AB



Class-AB push–pull amplifier

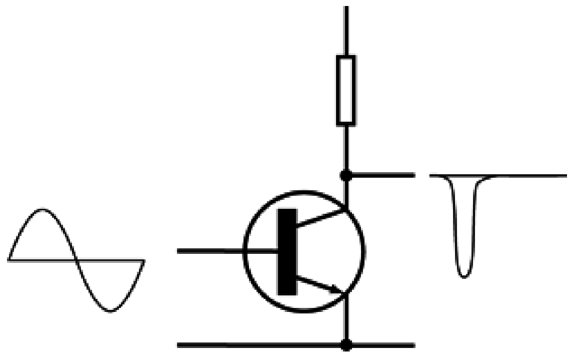
Class AB is widely considered a good compromise for amplifiers, since much of the time the music signal is quiet enough that the signal stays in the “class A” region, where it is amplified with good fidelity, and by definition if passing out of this region, is large enough that the distortion products typical of class B are relatively small. The crossover distortion can be reduced further by using negative feedback.

In class-AB operation, each device operates the same way as in class B over half the waveform, but also conducts a small amount on the other half. As a result, the region where both devices simultaneously are nearly off (the “dead zone”) is reduced. The result is that when the waveforms from the two devices are combined, the crossover is greatly minimised or eliminated altogether. The exact choice of **quiescent current** (the standing current through both devices when there is no signal) makes a large difference to the level of distortion (and to the risk of thermal runaway, that may damage the devices). Often, bias voltage applied to set this quiescent current must be adjusted with the temperature of the output transistors. (For example, in the circuit at the beginning of the article, the diodes would be mounted physically close to the output transistors, and specified to have a matched temperature coefficient.) Another approach (often used with thermally tracking bias voltages) is to include small value resistors in series with the emitters.

Class AB sacrifices some efficiency over class B in favor of linearity, thus is less efficient (below 78.5% for full-amplitude sinewaves in transistor amplifiers, typically; much less is common in class-AB vacuum-tube amplifiers). It is typically much more efficient than class A.

Sometimes a numeral is added for vacuum-tube stages. If grid current is not permitted to flow, the class is AB_1. If grid current is allowed to flow (adding more distortion, but giving slightly higher output power) the class is AB_2.

Class C



Class-C amplifier

Class-C amplifiers conduct less than 50% of the input signal and the distortion at the output is high, but high efficiencies (up to 90%) are possible. The usual application for class-C amplifiers is in RF transmitters operating at a single fixed carrier frequency, where the distortion is controlled by a tuned load on the amplifier. The input signal is used to switch the active device causing pulses of current to flow through a tuned circuit forming part of the load.

The class-C amplifier has two modes of operation: tuned and untuned.[16] The diagram shows a waveform from a simple class-C circuit without the tuned load. This is called untuned operation, and the analysis of the waveforms shows the massive distortion that appears in the signal. When the proper load (e.g., an inductive-capacitive filter plus a load resistor) is used, two things happen. The first is that the output's bias level is clamped with the average output voltage equal to the supply voltage. This is why tuned operation is sometimes called a *clamper*. This restores the waveform to its proper shape, despite the amplifier having only a one-polarity supply. This is directly related to the second phenomenon: the waveform on the center frequency becomes less distorted. The residual distortion is dependent upon the bandwidth of the tuned load, with the center frequency seeing very little distortion, but greater attenuation the farther from the tuned frequency that the signal gets.

The tuned circuit resonates at one frequency, the fixed carrier frequency, and so the unwanted frequencies are suppressed, and the wanted full signal (sine wave) is extracted by the tuned load. The signal bandwidth of the amplifier is limited by the Q-factor of the tuned circuit but this is not a serious limitation. Any residual harmonics can be removed using a further filter.

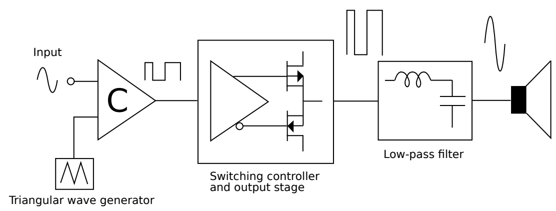
In practical class-C amplifiers a tuned load is invariably used. In one common arrangement the resistor shown in the circuit above is replaced with a parallel-tuned circuit consisting of an inductor and capacitor in parallel, whose components are chosen to resonate the frequency of the input signal. Power can be coupled to a load by transformer action with a secondary coil wound on the inductor. The average voltage at the drain is then equal to the supply voltage, and the signal voltage appearing across the tuned circuit varies from near zero to near twice the supply voltage during the rf cycle. The input circuit is biased so that the active element (e.g., transistor) conducts for only a fraction of the RF cycle, usually one third (120 degrees) or less.[17]

The active element conducts only while the drain voltage is passing through its minimum. By this means, power dissipation in the active device is minimised, and efficiency increased. Ideally, the active element would pass only an instantaneous current pulse while the voltage across it is zero: it then dissipates no power and 100% efficiency is achieved. However practical devices have a limit to the peak current they can pass, and the pulse must therefore be widened, to around 120 degrees, to obtain a reasonable amount of power, and the efficiency is then 60–70%.[17]

Class D

Main article: Class D amplifier

In the class-D amplifier the active devices (transistors)



Block diagram of a basic switching or PWM (class-D) amplifier.

function as electronic switches instead of linear gain devices; they are either on or off. The analog signal is converted to a stream of pulses that represents the signal by pulse width modulation, pulse density modulation, delta-sigma modulation or a related modulation technique before being applied to the amplifier. The time average power value of the pulses is directly proportional to the

Boss Audio class-D mono amplifier with a low pass filter for powering subwoofers

analog signal, so after amplification the signal can be converted back to an analog signal by a passive low-pass filter. The purpose of the output filter is to smooth the pulse stream to an analog signal, removing the high frequency spectral components of the pulses. The frequency of the output pulses is typically ten or more times the highest frequency in the input signal to amplify, so that the filter can adequately reduce the unwanted harmonics and accurately reproduce the input.

The main advantage of a class-D amplifier is power efficiency. Because the output pulses have a fixed amplitude, the switching elements (usually MOSFETs, but vacuum tubes, and at one time bipolar transistors, were used) are switched either completely on or completely off, rather than operated in linear mode. A MOSFET operates with the lowest resistance when fully on and thus (excluding when fully off) has the lowest power dissipation when in that condition. Compared to an equivalent class-AB device, a class-D amplifier's lower losses permit the use of a smaller heat sink for the MOSFETs while also reducing the amount of input power required, allowing for a lower-capacity power supply design. Therefore, class-D amplifiers are typically smaller than an equivalent class-AB amplifier.

Another advantage of the class-D amplifier is that it can operate from a digital signal source without requiring a digital-to-analog converter (DAC) to convert the signal to analog form first. If the signal source is in digital form, such as in a digital media player or computer sound card, the digital circuitry can convert the binary digital signal directly to a pulse width modulation signal that is applied to the amplifier, simplifying the circuitry considerably.

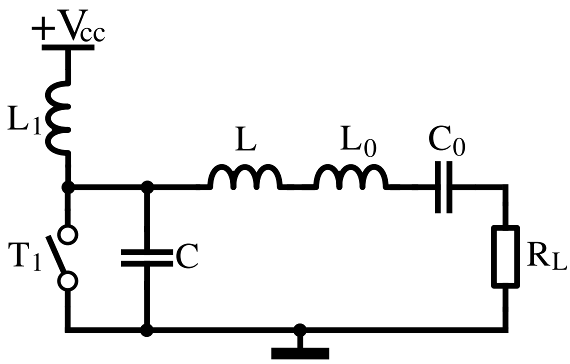
Class-D amplifiers are widely used to control motors—but are now also used as power amplifiers, with extra circuitry that converts analogue to a much higher frequency pulse width modulated signal. Switching power supplies have even been modified into crude class-D amplifiers (though typically these only reproduce low-frequencies with acceptable accuracy).

High quality class-D audio power amplifiers have now appeared on the market. These designs have been said to rival traditional AB amplifiers in terms of quality. An early use of class-D amplifiers was high-power subwoofer amplifiers in cars. Because subwoofers are generally limited to a bandwidth of no higher than 150 Hz, switching speed for the amplifier does not have to be as high as for a full range amplifier, allowing simpler designs. Class-D amplifiers for driving subwoofers are relatively inexpensive in comparison to class-AB amplifiers.

The letter *D* used to designate this amplifier class is simply the next letter after *C* and, although occasionally used as such, does not stand for *digital*. Class-D and class-E amplifiers are sometimes mistakenly described as "digital" because the output waveform superficially resembles a pulse-train of digital symbols, but a class-D amplifier merely converts an input waveform into a continuously pulse-width modulated analog signal. (A digital waveform would be pulse-code modulated.)

Additional classes

Class E The class-E/F amplifier is a highly efficient switching power amplifier, typically used at such high frequencies that the switching time becomes comparable to the duty time. As said in the class-D amplifier, the transistor is connected via a serial LC circuit to the load, and connected via a large L (inductor) to the supply voltage. The supply voltage is connected to ground via a large capacitor to prevent any RF signals leaking into the supply. The class-E amplifier adds a C (capacitor) between the transistor and ground and uses a defined L_1 to connect to the supply voltage.



Class-E amplifier

The following description ignores DC, which can be added easily afterwards. The above-mentioned C and L are in effect a parallel LC circuit to ground. When the transistor is on, it pushes through the serial LC circuit into the load and some current begins to flow to the parallel LC circuit to ground. Then the serial LC circuit swings back and compensates the current into the parallel LC circuit. At this point the current through the transistor is zero and it is switched off. Both LC circuits are now filled with energy in C and L_0. The whole circuit performs a damped oscillation. The damping by the load has been adjusted so that some time later the energy from the Ls is gone into the load, but the energy in both C_0 peaks at the original value to in turn restore the original voltage so that the voltage across the transistor is zero again and it can be switched on.

With load, frequency, and duty cycle (0.5) as given parameters and the constraint that the voltage is not only restored, but peaks at the original voltage, the four parameters (L, L_0, C and C_0) are determined. The class-E amplifier takes the finite on resistance into account and tries to make the current touch the bottom at zero. This means that the voltage and the current at the transistor are symmetric with respect to time. The Fourier transform allows an elegant formulation to generate the complicated LC networks and says that the first harmonic is passed into the load, all even harmonics are shorted and all higher odd harmonics are open.

Class E uses a significant amount of second-harmonic voltage. The second harmonic can be used to reduce the overlap with edges with finite sharpness. For this to work, energy on the second harmonic has to flow from the load into the transistor, and no source for this is visible in the circuit diagram. In reality, the impedance is mostly reactive and the only reason for it is that class E is a class F (see below) amplifier with a much simplified load network and thus has to deal with imperfections.

In many amateur simulations of class-E amplifiers, sharp current edges are assumed nullifying the very motivation for class E and measurements near the transit frequency of the transistors show very symmetric curves, which look much similar to class-F simulations.

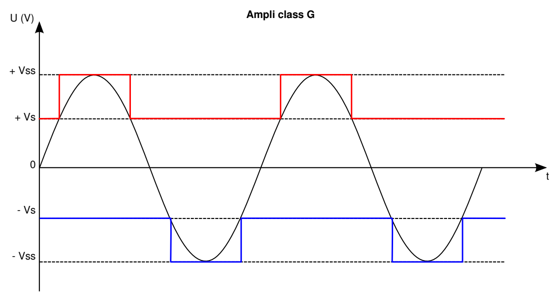
The class-E amplifier was invented in 1972 by Nathan O. Sokal and Alan D. Sokal, and details were first published in 1975.[18] Some earlier reports on this operating class have been published in Russian.

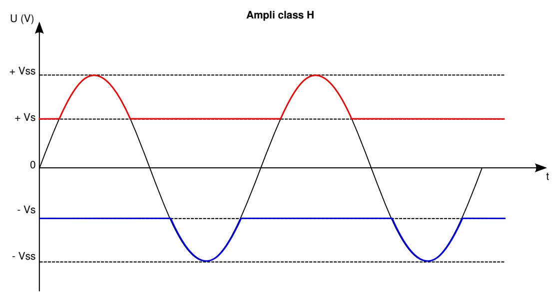
Class F In push–pull amplifiers and in CMOS, the even harmonics of both transistors just cancel. Experiment shows that a square wave can be generated by those amplifiers. Theoretically square waves consist of odd harmonics only. In a class-D amplifier, the output filter blocks all harmonics; i.e., the harmonics see an open load. So even small currents in the harmonics suffice to generate a voltage square wave. The current is in phase with the voltage applied to the filter, but the voltage across the transistors is out of phase. Therefore, there is a minimal overlap between current through the transistors and voltage across the transistors. The sharper the edges, the lower the overlap.

While in class D, transistors and the load exist as two separate modules, class F admits imperfections like the parasitics of the transistor and tries to optimise the global system to have a high impedance at the harmonics. Of course there must be a finite voltage across the transistor to push the current across the on-state resistance. Because the combined current through both transistors is mostly in the first harmonic, it looks like a sine. That means that in the middle of the square the maximum of current has to flow, so it may make sense to have a dip in the square or in other words to allow some overswing of the voltage square wave. A class-F load network by definition has to transmit below a cutoff frequency and reflect above.

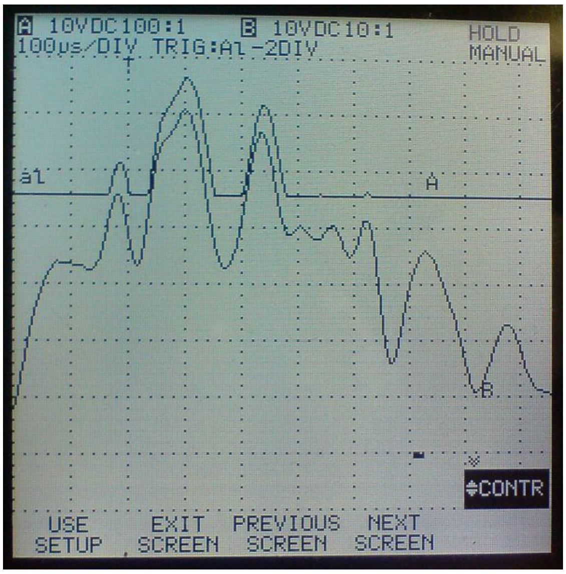
Any frequency lying below the cutoff and having its second harmonic above the cutoff can be amplified, that is an octave bandwidth. On the other hand, an inductive-capacitive series circuit with a large inductance and a tunable capacitance may be simpler to implement. By reducing the duty cycle below 0.5, the output amplitude can be modulated. The voltage square waveform degrades, but any overheating is compensated by the lower overall power flowing. Any load mismatch behind the filter can only act on the first harmonic current waveform, clearly only a purely resistive load makes sense, then the lower the resistance, the higher the current.

Class F can be driven by sine or by a square wave, for a sine the input can be tuned by an inductor to increase gain. If class F is implemented with a single transistor, the filter is complicated to short the even harmonics. All previous designs use sharp edges to minimise the overlap.

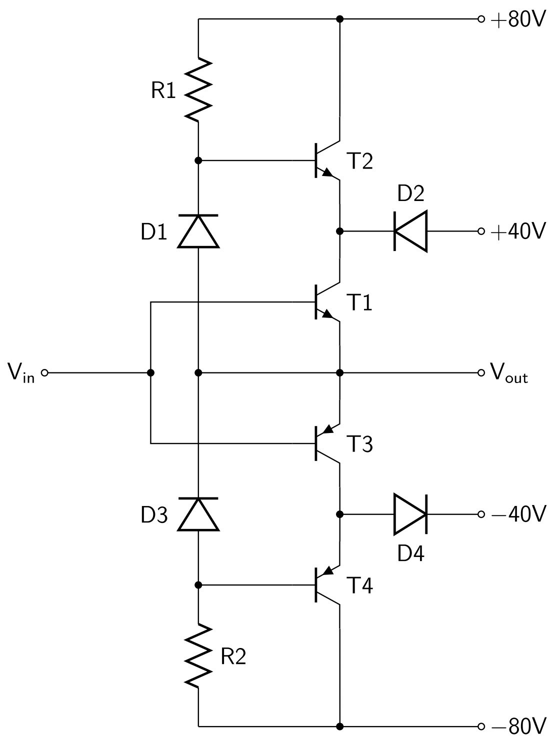




Classes G and H There is a variety of amplifier designs that enhance class-AB output stages with more efficient techniques **to achieve greater efficiencies with low distortion**. These designs are common in large audio amplifiers since the heatsinks and power transformers would be prohibitively large (and costly) without the efficiency increases. The terms “class G” and “class H” are



Rail voltage modulation



Basic schematic of a class-H configuration

used interchangeably to refer to different designs, varying in definition from one manufacturer or paper to another.

Class-G amplifiers (which use "rail switching" to decrease power consumption and increase efficiency) are more efficient than class-AB amplifiers. These amplifiers provide several power rails at different voltages and switch between them as the signal output approaches each level. Thus, the amplifier increases efficiency by reducing the wasted power at the output transistors. Class-G amplifiers are more efficient than class AB but less efficient when compared to class D, however, they do not have the electromagnetic interference effects of class D.

Class-H amplifiers take the idea of class G one step further creating an infinitely variable supply rail. This is done by modulating the supply rails so that the rails are only a few volts larger than the output signal at any given time. The output stage operates at its maximum efficiency all the time. Switched-mode power supplies can be used to create the tracking rails. Significant efficiency gains can be achieved but with the drawback of more complicated supply design and reduced THD performance. In common designs, a voltage drop of about 10V is maintained over the output transistors in Class H circuits. The picture above shows positive supply voltage of the output stage and the voltage at the speaker output. The boost of the supply voltage is shown for a real music signal.

The voltage signal shown is thus a larger version of the input, but has been changed in sign (inverted) by the amplification. Other arrangements of amplifying device are possible, but that given (that is, common emitter, common source or common cathode) is the easiest to understand and employ in practice. If the amplifying element is linear, the output is a faithful copy of the input, only larger and inverted. In practice, transistors are not linear, and the output only approximates the input. nonlinearity from any of several sources is the origin of distortion within an amplifier. The class of amplifier (A, B, AB or C) depends on how the amplifying device is biased. The diagrams omit the bias circuits for clarity.

Any real amplifier is an imperfect realization of an ideal amplifier. An important limitation of a real amplifier is that the output it generates is ultimately limited by the power available from the power supply. An amplifier saturates and clips the output if the input signal becomes too large for the amplifier to reproduce or exceeds operational limits for the device.

Doherty amplifiers Main article: Doherty amplifier

The Doherty, a hybrid configuration, is currently receiving renewed attention. It was invented in 1934 by William H. Doherty for Bell Laboratories—whose sister company, Western Electric, manufactured radio transmitters. The Doherty amplifier consists of a class-B *primary* or *carrier* stages in parallel with a class-C *auxiliary* or *peak* stage. The input signal splits to drive the two amplifiers, and a combining network sums the two output signals. Phase shifting networks are used in inputs and outputs. During periods of low signal level, the class-B amplifier efficiently operates on the signal and the class-C amplifier is cutoff and consumes little power. During periods of high signal level, the class-B amplifier delivers its maximum power and the class-C amplifier delivers up to its maximum power. The efficiency of previous AM transmitter designs was proportional to modulation but, with average modulation typically around 20%, transmitters were limited to less than 50% efficiency. In Doherty's design, even with zero modulation, a transmitter could achieve at least 60% efficiency.[19]

As a successor to Western Electric for broadcast transmitters, the Doherty concept was considerably refined by Continental Electronics Manufacturing Company of Dallas, TX. Perhaps, the ultimate refinement was the screen-grid modulation scheme invented by Joseph B. Sainton. The Sainton amplifier consists of a class-C primary or carrier stage in parallel with a class-C auxiliary or peak stage. The stages are split and combined through 90-degree phase shifting networks as in the Doherty amplifier. The unmodulated radio frequency carrier is applied to the control grids of both tubes. Carrier modulation is applied to the screen grids of both tubes. The bias point of the carrier and peak tubes is different, and is established such that the peak tube is cutoff when modulation is absent (and the amplifier is producing rated unmodulated carrier power) whereas both tubes contribute twice the rated carrier power during 100% modulation (as four times the carrier power is required to achieve 100% modulation). As both tubes operate in class C, a significant improvement in efficiency is thereby achieved in the final stage. In addition, as the tetrode carrier and peak tubes require very little drive power, a significant improvement in efficiency within the driver stage is achieved as well (317C, et al.).[20] The released version of the Sainton amplifier employs a cathode-follower modulator, not a push–pull modulator. Previous Continental Electronics designs, by James O. Weldon and others, retained most of the characteristics of the Doherty amplifier but added screen-grid modulation of the driver (317B, et al.).

The Doherty amplifier remains in use in very-high-power AM transmitters, but for lower-power AM transmitters, vacuum-tube amplifiers in general were eclipsed in the 1980s by arrays of solid-state amplifiers, which could be switched on and off with much finer granularity in response to the requirements of the input audio. However, interest in the Doherty configuration has been revived by cellular-telephone and wireless-Internet applications where the sum of several constant envelope users creates an aggregate AM result. The main challenge of the Doherty amplifier for digital transmission modes is in aligning the two stages and getting the class-C amplifier to turn on and off very quickly.

Recently, Doherty amplifiers have found widespread use in cellular base station transmitters for GHz frequencies. Implementations for transmitters in mobile devices have also been demonstrated.

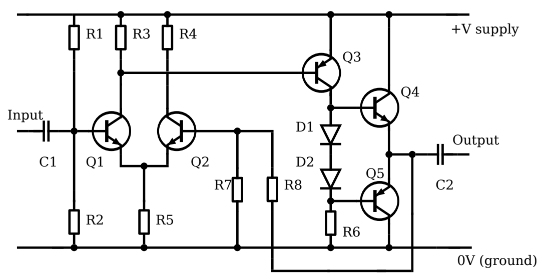
5.3.5 Implementation

Amplifiers are implemented using active elements of different kinds:

- The first active elements were relays. They were for example used in transcontinental telegraph lines: a weak current was used to switch the voltage of a battery to the outgoing line.
- For transmitting audio, carbon microphones were used as the active element. This was used to modulate a radio-frequency source in one of the first AM audio transmissions, by Reginald Fessenden on Dec. 24, 1906.[21]
- Power control circuitry used magnetic amplifiers until the latter half of the twentieth century when high power FETs, and their easy interfacing to the newly developed digital circuitry, took over.
- Audio and most low power amplifiers used vacuum tubes exclusively until the 1960s. Today, tubes are used for specialist audio applications such as guitar amplifiers and audiophile amplifiers. Many broadcast transmitters still use vacuum tubes.
- In the 1960s, the transistor started to take over. These days, discrete transistors are still used in high-power amplifiers and in specialist audio devices.
- Beginning in the 1970s, more and more transistors were connected on a single chip therefore creating the integrated circuit. A large number of amplifiers commercially available today are based on integrated circuits.

For special purposes, other active elements have been used. For example, in the early days of the satellite communication, parametric amplifiers were used. The core circuit was a diode whose capacitance was changed by an RF signal created locally. Under certain conditions, this RF signal provided energy that was modulated by the extremely weak satellite signal received at the earth station.

Amplifier circuit



A practical amplifier circuit

The practical amplifier circuit to the right could be the basis for a moderate-power audio amplifier. It features a typical (though substantially simplified) design as found in modern amplifiers, with a class-AB push–pull output stage, and uses some overall negative feedback. Bipolar transistors are shown, but this design would also be realizable with FETs or valves.

The input signal is coupled through capacitor C1 to the base of transistor Q1. The capacitor allows the AC signal to pass, but blocks the DC bias voltage established by resistors R1 and R2 so that any preceding circuit is not affected by it. Q1 and Q2 form a differential amplifier (an amplifier that multiplies the difference between two inputs by some constant), in an arrangement known as a long-tailed pair. This arrangement is used to conveniently allow the use of negative feedback, which is fed from the output to Q2 via R7 and R8.

The negative feedback into the difference amplifier allows the amplifier to compare the input to the actual output. The amplified signal from Q1 is directly fed to the second stage, Q3, which is a common emitter stage that provides further amplification of the signal and the DC bias for the output stages, Q4 and Q5. R6 provides the load for Q3 (a better design would probably use some form of active load here, such as a constant-current sink). So far, all of the amplifier is operating in class A. The output pair are arranged in class-AB push–pull, also called a complementary pair. They provide the majority of the current amplification (while consuming low quiescent current) and directly drive the load, connected via DC-blocking capacitor C2. The diodes D1 and D2 provide a small amount of constant voltage bias for the output pair, just biasing them into the conducting state so that crossover distortion is minimized. That is, the diodes push the output stage firmly into class-AB mode (assuming that the base-emitter drop of the output transistors is reduced by heat dissipation).

This design is simple, but a good basis for a practical design because it automatically stabilises its operating point, since feedback internally operates from DC up through the audio range and beyond. Further circuit elements would probably be found in a real design that would roll-off the frequency response above the needed range to prevent the possibility of unwanted oscillation. Also, the use of fixed diode bias as shown here can cause problems if the diodes are not both electrically and thermally matched to the output transistors – if the output transistors turn on too much, they can easily overheat and destroy themselves, as the full current from the power supply is not limited at this stage.

A common solution to help stabilise the output devices is to include some emitter resistors, typically one ohm or so. Calculating the values of the circuit's resistors and capacitors is done based on the components employed and the intended use of the amp.

Two most common circuits:[22]

- A Cascode amplifier is a two-stage circuit consisting of a transconductance amplifier followed by a buffer amplifier.
- A Log amplifier is a linear circuit in which output voltage is a constant times the natural logarithm of input.

For the basics of radio frequency amplifiers using valves, see Valved RF amplifiers.

Notes on implementation

Real world amplifiers are imperfect.

- The power supply may influence the output, so must be considered in the design.
- A power amplifier is effectively an input signal controlled power regulator. It regulates the power sourced from the power supply or mains to the amplifier's load. The power output from a power amplifier cannot exceed the power input to it.
- The amplifier circuit has an “open loop” performance. This is described by various parameters (gain, slew rate, output impedance, distortion, bandwidth, signal to noise ratio, etc.).
- Many modern amplifiers use negative feedback techniques to hold the gain at the desired value and reduce distortion. Negative loop feedback has the intended effect of electrically damping loudspeaker motion, thereby damping the mechanical dynamic performance of the loudspeaker.
- When assessing rated amplifier power output, it is useful to consider the applied load, the signal type (e.g., speech or music), required power output duration (i.e., short-time or continuous), and required dynamic range (e.g., recorded or live audio).
- In high-powered audio applications that require long cables to the load (e.g., cinemas and shopping centres) it may be more efficient to connect to the load at line output voltage, with matching transformers at source and loads. This avoids long runs of heavy speaker cables.
- Prevent instability or overheating requires care to ensure solid state amplifiers are adequately loaded. Most have a rated minimum load impedance.
- A summing circuit is typical in applications that must combine many inputs or channels to form a composite output. It is best to combine multiple channels for this.[23]
- All amplifiers generate heat through electrical losses. The amplifier must dissipate this heat via convection or forced air cooling. Heat can damage or reduce electronic component service life. Designers and installers must also consider heating effects on adjacent equipment.

Different power supply types result in many different methods of bias. Bias is a technique by which active devices are set to operate in a particular region, or by which the DC component of the output signal is set to the midpoint between the maximum voltages available from the power supply. Most amplifiers use several devices at each stage; they are typically matched in specifications except for polarity. Matched inverted polarity devices are called complementary pairs. Class-A amplifiers generally use only one device, unless the power supply is set to provide both positive and negative voltages, in which case a dual device symmetrical design may be used. Class-C amplifiers, by definition, use a single polarity supply.

Amplifiers often have multiple stages in cascade to increase gain. Each stage of these designs may be a different type of amp to suit the needs of that stage. For instance, the first stage might be a class-A stage, feeding a class-AB push–pull second stage, which then drives a class-G final output stage, taking advantage of the strengths of each type, while minimizing their weaknesses.

5.3.6 See also

- Class-T amplifier
- Charge transfer amplifier
- Distributed amplifier
- Faithful amplification
- Guitar amplifier
- Instrument amplifier
- Instrumentation amplifier
- Low noise amplifier
- Magnetic amplifier
- Negative feedback amplifier
- Operational amplifier
- Optical amplifier
- Power added efficiency
- Programmable gain amplifier
- RF power amplifier
- Valve audio amplifier

5.3.7 References

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5.3.8 External links

- Rane audio’s guide to amplifier classes
- Design and analysis of a basic class D amplifier
- Conversion: distortion factor to distortion attenuation and THD
- An alternate topology called the grounded bridge amplifier - pdf
- Contains an explanation of different amplifier classes - pdf
- Reinventing the power amplifier - pdf
- Anatomy of the power amplifier, including information about classes
- Tons of Tones - Site explaining non linear distortion stages in Amplifier Models
- Class D audio amplifiers, white paper - pdf
- Class E Radio Transmitters - Tutorials, Schematics, Examples, and Construction Details

5.4 Operational amplifier

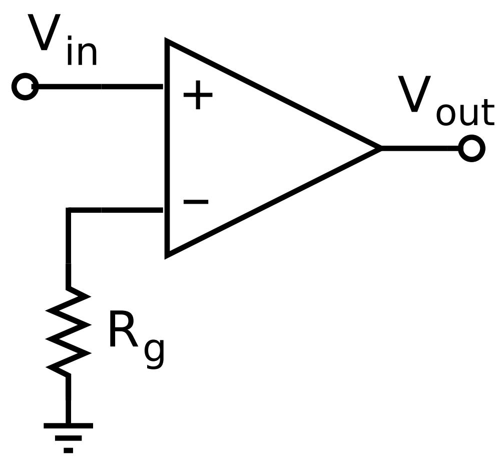
An **operational amplifier** (often **op-amp** or **opamp**) is a DC-coupled high-gain electronic voltage amplifier with a differential input and, usually, a single-ended output.[1] In this configuration, an op-amp produces an output potential (relative to circuit ground) that is typically hundreds of thousands of times larger than the potential difference between its input terminals.[2]

Operational amplifiers had their origins in analog computers, where they were used to do mathematical operations in many linear, non-linear and frequency-dependent circuits. The popularity of the op-amp as a building block in analog circuits is due to its versatility. Due to negative feedback, the characteristics of an op-amp circuit, its gain, input and output impedance, bandwidth etc. are determined by external components and have little dependence on temperature coefficients or manufacturing variations in the op-amp itself.

Op-amps are among the most widely used electronic devices today, being used in a vast array of consumer, industrial, and scientific devices. Many standard IC op-amps cost only a few cents in moderate production volume; however some integrated or hybrid operational amplifiers with special performance specifications may cost over $100 US in small quantities.[3] Op-amps may be packaged as components, or used as elements of more complex integrated circuits.

The op-amp is one type of differential amplifier. Other types of differential amplifier include the fully differential amplifier (similar to the op-amp, but with two outputs), the instrumentation amplifier (usually built from three op-amps), the isolation amplifier (similar to the instrumentation amplifier, but with tolerance to common-mode voltages that would destroy an ordinary op-amp), and negative feedback amplifier (usually built from one or more op-amps and a resistive feedback network).

5.4.1 Operation



An op-amp without negative feedback (a comparator)

The amplifier’s differential inputs consist of a non-inverting input (+) with voltage V_+ and an inverting input (–) with voltage V_-; ideally the op-amp amplifies only the difference in voltage between the two, which is called the *differential input voltage*. The output voltage of the op-amp V_{out} is given by the equation:

$$V_{\text{out}} = A_{\text{OL}}\,(V_+ - V_-)$$

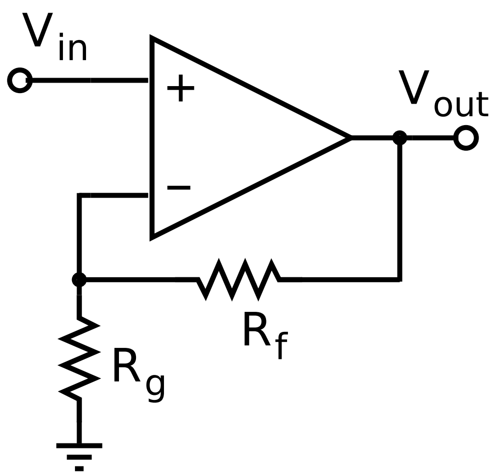
where AOL is the open-loop gain of the amplifier (the term "open-loop" refers to the absence of a feedback loop from the output to the input).

Open loop amplifier

The magnitude of AOL is typically very large—100,000 or more for integrated circuit op-amps—and therefore even a quite small difference between V_+ and V_- drives the amplifier output nearly to the supply voltage. Situations in which the output voltage is equal to or greater than the supply voltage are referred to as *saturation* of the amplifier. The magnitude of AOL is not well controlled by the manufacturing process, and so it is impractical to use an open loop amplifier as a stand-alone differential amplifier.

Without negative feedback, and perhaps with positive feedback for regeneration, an op-amp acts as a comparator. If the inverting input is held at ground (0 V) directly or by a resistor R_g, and the input voltage V_{in} applied to the non-inverting input is positive, the output will be maximum positive; if V_{in} is negative, the output will be maximum negative. Since there is no feedback from the output to either input, this is an *open loop* circuit acting as a comparator.

Closed loop



An op-amp with negative feedback (a non-inverting amplifier)

If predictable operation is desired, negative feedback is used, by applying a portion of the output voltage to the inverting input. The *closed loop* feedback greatly reduces the gain of the circuit. When negative feedback is used, the circuit's overall gain and response becomes determined mostly by the feedback network, rather than by the op-amp characteristics. If the feedback network is made of components with values small relative to the op amp's input impedance, the value of the op-amp's open loop response AOL does not seriously affect the circuit's performance. The response of the op-amp circuit with its input, output, and feedback circuits to an input is characterized mathematically by a transfer function; designing an op-amp circuit to have a desired transfer function is in the realm of electrical engineering. The transfer functions are important in most applications of op-amps, such as in analog computers. High input impedance at the input terminals and low output impedance at the output terminal(s) are particularly useful features of an op-amp.

In the non-inverting amplifier on the right, the presence of negative feedback via the voltage divider R_f, R_g determines the *closed-loop gain* ACL = V_{out} / V_{in}. Equilibrium will be established when V_{out} is just sufficient to "reach around and pull" the inverting input to the same voltage as V_{in}. The voltage gain of the entire circuit is thus 1 + R_f/R_g. As a simple example, if V_{in} = 1 V and R_f = R_g, V_{out} will be 2 V, exactly the amount required to keep V_- at 1 V. Because of the feedback provided by the R_f, R_g network, this is a *closed loop* circuit.

Another way to analyze this circuit proceeds by making the following (usually valid) assumptions:[4]

- When an op-amp operates in linear (i.e., not saturated) mode, the difference in voltage between the non-inverting (+) pin and the inverting (−) pin is negligibly small.
- The input impedance between (+) and (−) pins is much larger than other resistances in the circuit.

The input signal V_{in} appears at both (+) and (−) pins, resulting in a current i through R_g equal to V_{in}/R_g.

$$i = \frac{V_{\text{in}}}{R_g}$$

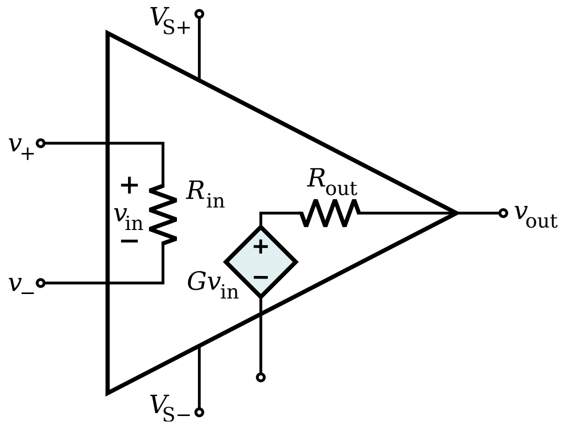
Since Kirchhoff's current law states that the same current must leave a node as enter it, and since the impedance into the (−) pin is near infinity, we can assume practically all of the same current i flows through R_f, creating an output voltage

$$V_{\text{out}} = V_{\text{in}} + i \times R_f = V_{\text{in}} + \left(\frac{V_{\text{in}}}{R_g} \times R_f\right) = V_{\text{in}} + \frac{V_{\text{in}} \times R_f}{R_g} = V_{\text{in}}\left(1 + \frac{R_f}{R_g}\right)$$

By combining terms, we determine the closed-loop gain ACL:

$$A_{\text{CL}} = \frac{V_{\text{out}}}{V_{\text{in}}} = 1 + \frac{R_f}{R_g}$$

5.4.2 Op-amp characteristics



An equivalent circuit of an operational amplifier that models some resistive non-ideal parameters.

Ideal op-amps

An ideal op-amp is usually considered to have the following properties:

- Infinite open-loop gain G = v_{out} / 'vin
- Infinite input impedance R_{in}, and so zero input current
- Zero input offset voltage
- Infinite voltage range available at the output
- Infinite bandwidth with zero phase shift and infinite slew rate
- Zero output impedance R_{out}
- Zero noise
- Infinite Common-mode rejection ratio (CMRR)
- Infinite Power supply rejection ratio.

These ideals can be summarized by the two "golden rules":

I. **In a closed loop** the output attempts to do whatever is necessary to make the voltage difference between the inputs zero.

II. The inputs draw no current.[5]:177

The first rule only applies in the usual case where the op-amp is used in a closed-loop design (negative feedback, where there is a signal path of some sort feeding back from the output to the inverting input). These rules are commonly used as a good first approximation for analyzing or designing op-amp circuits.[5]:177

None of these ideals can be perfectly realized. A real op-amp may be modeled with non-infinite or non-zero parameters using equivalent resistors and capacitors in the op-amp model. The designer can then include these effects into the overall performance of the final circuit. Some parameters may turn out to have negligible effect on the final design while others represent actual limitations of the final performance that must be evaluated.

Real op-amps

Real op-amps differ from the ideal model in various aspects.

DC imperfections Real operational amplifiers suffer from several non-ideal effects:

Finite gain Open-loop gain is infinite in the ideal operational amplifier but finite in real operational amplifiers. Typical devices exhibit open-loop DC gain ranging from 100,000 to over 1 million. So long as the loop gain (i.e., the product of open-loop and feedback gains) is very large, the circuit gain will be determined entirely by the amount of negative feedback (i.e., it will be independent of open-loop gain). In cases where closed-loop gain must be very high, the feedback gain will be very low, and the low feedback gain causes low loop gain; in these cases, the operational amplifier will cease to behave ideally.

Finite input impedances The *differential input impedance* of the operational amplifier is defined as the impedance *between* its two inputs; the *common-mode input impedance* is the impedance from each input to ground. MOSFET-input operational amplifiers often have protection circuits that effectively short circuit any input differences greater than a small threshold, so the input impedance can appear to be very low in some tests. However, as long as these operational amplifiers are used in a typical high-gain negative feedback application, these protection circuits will be inactive. The input bias and leakage currents described below are a more important design parameter for typical operational amplifier applications.

Non-zero output impedance Low output impedance is important for low-impedance loads; for these loads, the voltage drop across the output impedance effectively reduces the open loop gain. In configurations with a voltage-sensing negative feedback, the output impedance of the amplifier is effectively lowered; thus, in linear applications, op-amp circuits usually exhibit a very low output impedance indeed.

Low-impedance outputs typically require high quiescent (i.e., idle) current in the output stage and will dissipate more power, so low-power designs may purposely sacrifice low output impedance.

Input current Due to biasing requirements or leakage, a small amount of current (typically ~10 nanoamperes for bipolar op-amps, tens of picoamperes (pA) for JFET input stages, and only a few pA for MOSFET input stages) flows into the inputs. When large resistors or sources with high output impedances are used in the circuit, these small currents can produce large unmodeled voltage drops. If the input currents are matched, *and* the impedance looking *out* of *both* inputs are matched, then the voltages produced at each input will be equal. Because the operational amplifier operates on the *difference* between its inputs, these matched voltages will have no effect. It is more common for the input currents to be slightly mismatched. The difference is called input offset current, and even with matched resistances a small *offset voltage* (different from the input offset voltage below) can be produced. This offset voltage can create offsets or drifting in the operational amplifier.

Input offset voltage This voltage, which is what is required across the op-amp's input terminals to drive the output voltage to zero.[6][nb 1] In the perfect amplifier, there would be no input offset voltage. However, it exists in actual op-amps because of imperfections in the differential amplifier that constitutes the input stage of the vast majority of these devices. Input offset voltage creates two problems: First, due to the amplifier's high voltage gain, it virtually assures that the amplifier output will go into saturation if it is operated without negative feedback, even when the input terminals are wired together. Second, in a closed loop, negative feedback configuration, the input offset voltage is amplified along with the signal and this may pose a problem if high precision DC amplification is required or if the input signal is very small.[nb 2]

Common-mode gain A perfect operational amplifier amplifies only the voltage difference between its two inputs, completely rejecting all voltages that are common to both. However, the differential input stage of an operational amplifier is never perfect, leading to the amplification of these common voltages to some degree. The standard measure of this defect is called the common-mode rejection ratio (denoted CMRR). Minimization of common mode gain is usually important in non-inverting amplifiers (described below) that operate at high amplification.

Power-supply rejection The output of a perfect operational amplifier will be completely independent from its power supply. Every real operational amplifier has a finite power supply rejection ratio (PSRR) that reflects how well the op-amp can reject changes in its supply voltage.

Temperature effects All parameters change with temperature. Temperature drift of the input offset voltage is especially important.

Drift Real op-amp parameters are subject to slow change over time and with changes in temperature, input conditions, etc.

AC imperfections The op-amp gain calculated at DC does not apply at higher frequencies. Thus, for high-speed operation, more sophisticated considerations must be used in an op-amp circuit design.

Finite bandwidth All amplifiers have finite bandwidth. To a first approximation, the op-amp has the frequency response of an integrator with gain. That is, the gain of a typical op-amp is inversely proportional to frequency and is characterized by its gain–bandwidth product (GBWP). For example, an op-amp with a GBWP of 1 MHz would have a gain of 5 at 200 kHz, and a gain of 1 at 1 MHz. This dynamic response coupled with the very high DC gain of the op-amp gives it the characteristics of a first-order low-pass filter with very high DC gain and low cutoff frequency given by the GBWP divided by the DC gain.

The finite bandwidth of an op-amp can be the source of several problems, including:

- **Stability**. Associated with the bandwidth limitation is a phase difference between the input signal and the amplifier output that can lead to oscillation in some feedback circuits. For example, a sinusoidal output signal meant to interfere destructively with an input signal of the same frequency will interfere constructively if delayed by 180 degrees forming positive feedback. In these cases, the feedback circuit can be stabilized by means of frequency compensation, which increases the gain or phase margin of the open-loop circuit. The circuit designer can implement this compensation externally with a separate circuit component. Alternatively, the compensation can be implemented within the operational amplifier with the addition of a dominant pole that sufficiently attenuates the high-frequency gain of the operational amplifier. The location of this pole may be fixed internally by the manufacturer or configured by the circuit designer using methods specific to the op-amp. In general, dominant-pole frequency compensation reduces the bandwidth of the op-amp even further. When the desired closed-loop gain is high, op-amp frequency compensation is often not needed because the requisite open-loop gain is sufficiently low; consequently, applications with high closed-loop gain can make use of op-amps with higher bandwidths.

- **Distortion, and Other Effects**. Limited bandwidth also results in lower amounts of feedback at higher frequencies, producing higher distortion, and output impedance as the frequency increases.

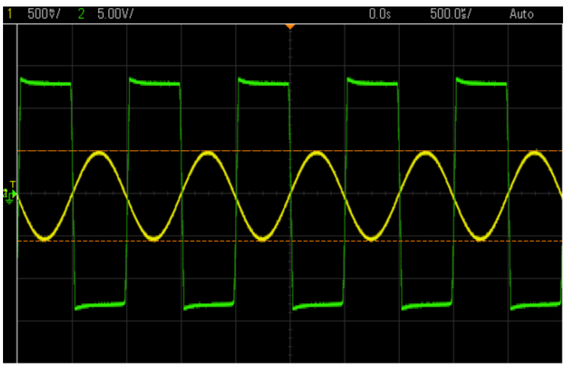
Typical low-cost, general-purpose op-amps exhibit a GBWP of a few megahertz. Specialty and high-speed op-amps exist that can achieve a GBWP of hundreds of megahertz. For very high-frequency circuits, a current-feedback operational amplifier is often used.

Noise Amplifiers generate random voltage at the output even when there is no signal applied. This can be due to thermal noise and flicker noise of the devices. For applications with high gain or high bandwidth, noise becomes a very important consideration.

Input capacitance Most important for high frequency operation because it reduces input impedance and may cause phase shifts.

Common-mode gain See DC imperfections, above.

Power-supply rejection With increasing frequency the power-supply rejection usually gets worse. So it can be important to keep the supply clean of higher frequency ripples and signals, e.g. by the use of bypass capacitors.



The input (yellow) and output (green) of a saturated op amp in an inverting amplifier

Non-linear imperfections

Saturation Output voltage is limited to a minimum and maximum value close to the power supply voltages.[nb 3] The output of older op-amps can reach to within one or two volts of the supply rails. The output of newer so-called “rail to rail” op-amps can reach to within millivolts of the supply rails when providing low output currents.

Slewing The amplifier’s output voltage reaches its maximum rate of change, the slew rate, usually specified in volts per microsecond. When slewing occurs, further increases in the input signal have no effect on the rate of change of the output. Slewing is usually caused by the input stage saturating; the result is a constant current i driving a capacitance C in the amplifier (especially those capacitances used to implement its frequency compensation); the slew rate is limited by $dv/dt=i/C$.

Slewing is associated with the *large-signal* performance of an op-amp. Consider for, example an op-amp configured for a gain of 10. Let the input be a 1 V, 100 kHz sawtooth wave. That is, the amplitude is 1 V and the period is 10 microseconds. Accordingly, the rate of change (i.e., the slope) of the input is 0.1 V per microsecond. After 10x amplification, the output should be a 10 V, 100 kHz sawtooth, with a corresponding slew rate of 1 V per microsecond. However, the classic 741 op-amp has a 0.5 V per microsecond slew rate specification, so that its output can rise to no more than 5 V in the sawtooth’s 10 microsecond period. Thus, if one were to measure the output, it would be a 5 V, 100 kHz sawtooth, rather than a 10 V, 100 kHz sawtooth.

Next consider the same amplifier and 100 kHz sawtooth, but now the input amplitude is 100 mV rather than 1 V. After 10x amplification the output is a 1 V, 100 kHz sawtooth with a corresponding slew rate of 0.1 V per microsecond. In this instance the 741 with its 0.5 V per microsecond slew rate will amplify the input properly.

Modern high speed op-amps can have slew rates in excess of 5,000 V per microsecond. However, it is more common for op-amps to have slew rates in the range 5-100 V per microsecond. For example, the general purpose TL081 op-amp has a slew rate of 13 V per microsecond. As a general rule, low power and small bandwidth op-amps have low slew rates. As an example, the LT1494 micropower op-amp consumes 1.5 microamp but has a 2.7 kHz gain-bandwidth product and a 0.001 V per microsecond slew rate.

Non-linear input-output relationship The output voltage may not be accurately proportional to the difference between the input voltages. It is commonly called distortion when the input signal is a waveform. This effect will be very small in a practical circuit where substantial negative feedback is used.

Phase reversal In some integrated op-amps, when the published common mode voltage is violated (e.g. by one of the inputs being driven to one of the supply voltages), the output may slew to the opposite polarity from what is expected in normal operation.[7][8] Under such conditions, negative feedback becomes positive, likely causing the circuit to "lock up" in that state.

Power considerations

Limited output current The output current must be finite. In practice, most op-amps are designed to limit the output current so as not to exceed a specified level – around 25 mA for a type 741 IC op-amp – thus protecting the op-amp and associated circuitry from damage. Modern designs are electronically more rugged than earlier implementations and some can sustain direct short circuits on their outputs without damage.

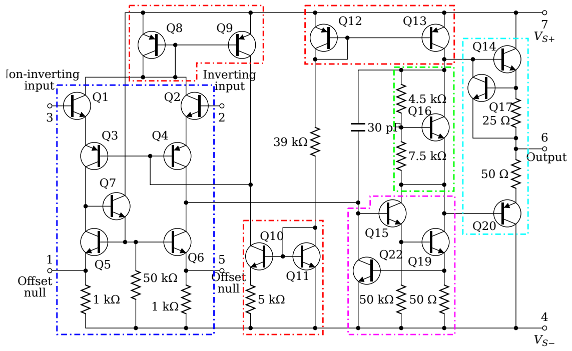
Output sink current The output sink current is the maximum current allowed to sink into the output stage. Some manufacturers show the output voltage vs. the output sink current plot, which gives an idea of the output voltage when it is sinking current from another source into the output pin.

Limited dissipated power The output current flows through the op-amp's internal output impedance, dissipating heat. If the op-amp dissipates too much power, then its temperature will increase above some safe limit. The op-amp may enter thermal shutdown, or it may be destroyed.

Modern integrated FET or MOSFET op-amps approximate more closely the ideal op-amp than bipolar ICs when it comes to input impedance and input bias currents. Bipolars are generally better when it comes to input *voltage* offset, and often have lower noise. Generally, at room temperature, with a fairly large signal, and limited bandwidth, FET and MOSFET op-amps now offer better performance.

5.4.3 Internal circuitry of 741-type op-amp

Sourced by many manufacturers, and in multiple similar products, an example of a bipolar transistor operational



A component-level diagram of the common 741 op-amp. Dotted lines outline: current mirrors (red); differential amplifier (blue); class A gain stage (magenta); voltage level shifter (green); output stage (cyan).

amplifier is the 741 integrated circuit designed in 1968 by David Fullagar at Fairchild Semiconductor after Bob Widlar's LM301 integrated circuit design.[9] In this discussion, we use the parameters of the Hybrid-pi model to characterize the small-signal, grounded emitter characteristics of a transistor. In this model, the current gain of a transistor is denoted h_{fe}, more commonly called the β.[10]

Architecture

A small-scale integrated circuit, the 741 op-amp shares with most op-amps an internal structure consisting of three gain stages:[11]

1. Differential amplifier (outlined blue) — provides high differential amplification (gain), with rejection of common-mode signal, low noise, high input impedance, and drives a
2. Voltage amplifier (outlined magenta) — provides high voltage gain, a single-pole frequency roll-off, and in turn drives the
3. Output amplifier (outlined cyan and green) — provides high current gain (low output impedance), along with output current limiting, and output short-circuit protection.

Additionally, it contains current mirror (outlined red) bias circuitry and a gain-stabilization capacitor (30 pF).

Differential amplifier The input stage consists of a cascaded differential amplifier (outlined in blue) followed by a current-mirror active load. This constitutes a transconductance amplifier, turning a differential voltage signal at the bases of Q1, Q2 into a current signal into the base of Q15.

It entails two cascaded transistor pairs, satisfying conflicting requirements. The first stage consists of the matched

NPN emitter follower pair Q1, Q2 that provide high input impedance. The second is the matched PNP common-base pair Q3, Q4 that eliminates the undesirable Miller effect; it drives an active load Q7 plus matched pair Q5, Q6.

That active load is implemented as a modified Wilson current mirror; its role is to convert the (differential) input current signal to a single-ended signal without the attendant 50% losses (increasing the op-amp's open-loop gain by 3 dB).[nb 4] Thus, a small-signal differential current in Q3 versus Q4 appears summed (doubled) at the base of Q15, the input of the voltage gain stage.

Voltage amplifier The (class-A) voltage gain stage (outlined in magenta) consists of the two NPN transistors Q15/Q19 connected in a Darlington configuration and uses the output side of current mirror Q12/Q13 as its collector (dynamic) load to achieve its high voltage gain. The output sink transistor Q20 receives its base drive from the common collectors of Q15 and Q19; the level-shifter Q16 provides base drive for the output source transistor Q14.
.

The transistor Q22 prevents this stage from delivering excessive current to Q20 and thus limits the output sink current.

Output amplifier The output stage (Q14, Q20, outlined in cyan) is a Class AB push-pull emitter follower amplifier. It provides an output drive with impedance of ≈50Ω, in essence, current gain. Transistor Q16 (outlined in green) provides the quiescent current for the output transistors, and Q17 provides output current limiting.

Biasing circuits

Provide appropriate quiescent current for each stage of the op-amp.

The resistor (39 kΩ) connecting the (diode-connected) Q11 and Q12, and the given supply voltage (VS_{+}–VS_{-}), determine the current in the current mirrors, (matched pairs) Q10/Q11 and Q12/Q13. The collector current of Q11, i_{11} * 39 kΩ = VS_{+} – VS_{-} – 2 VBE. For the typical VS = ±20 V, the standing current in Q11/Q12 (as well as in Q13) would be ≈1 mA. A supply current for a typical 741 of about 2 mA agrees with the notion that these two bias currents dominate the quiescent supply current.

Transistors Q11 and Q10 form a Widlar current mirror, with quiescent current in Q10 i_{10} such that ln(i_{11} / i_{10}) = i_{10} * 5 kΩ / 28 mV, where 5 kΩ represents the emitter resistor of Q10, and 28 mV is VT, the thermal voltage at room temperature. In this case i_{10} ≈ 20 μA.

Differential amplifier The biasing circuit of this stage is set by a feedback loop that forces the collector currents of Q10 and Q9 to (nearly) match. The small difference in these currents provides the drive for the common base of Q3/Q4 (note that the base drive for input transistors Q1/Q2 is the input bias current and must be sourced externally). The summed quiescent currents of Q1/Q3 plus Q2/Q4 is mirrored from Q8 into Q9, where it is summed with the collector current in Q10, the result being applied to the bases of Q3/Q4.

The quiescent currents of Q1/Q3 (resp., Q2/Q4) i_1 will thus be half of i_{10}, of order ≈ 10 μA. Input bias current for the base of Q1 (resp. Q2) will amount to i_1 / β; typically ≈50 nA, implying a current gain h_{fe} ≈ 200 for Q1(Q2).

This feedback circuit tends to draw the common base node of Q3/Q4 to a voltage V_{com} – 2 * VBE, where V_{com} is the input common-mode voltage. At the same time, the magnitude of the quiescent current is relatively insensitive to the characteristics of the components Q1–Q4, such as h_{fe}, that would otherwise cause temperature dependence or part-to-part variations.

Transistor Q7 drives Q5 and Q6 into conduction until their (equal) collector currents match that of Q1/Q3 and Q2/Q4. The quiescent current in Q7 is VBE / 50 kΩ, about 35μA, as is the quiescent current in Q15, with its matching operating point. Thus, the quiescent currents are pairwise matched in Q1/Q2, Q3/Q4, Q5/Q6, and Q7/Q15.

Voltage amplifier Quiescent currents in Q16 and Q19 are set by the current mirror Q12/Q13, which is running at ≈ 1 mA. Through some mechanism, the collector current in Q19 tracks that standing current.

Output amplifier In the circuit involving Q16 (variously named rubber diode or VBE multiplier), the 4.5 kΩ resistor must be conducting about 100 μA, with the Q16 VBE roughly 700 mV. Then the VCB must be about 0.45 V and VCE at about 1.0 V. Because the Q16 collector is driven by a current source and the Q16 emitter drives into the Q19 collector current sink, the Q16 transistor establishes a voltage difference between Q14 base and Q20 base of ≈ 1 V, regardless of the common-mode voltage of Q14/Q20 base. The standing current in Q14/Q20 will be a factor exp(100 mV / VT) ≈ 36 smaller than the 1 mA quiescent current in the class A portion of the op amp. This (small) standing current in the output transistors establishes the output stage in class AB operation and reduces the crossover distortion of this stage.

Small-signal differential mode

A small differential input voltage signal gives rise, through multiple stages of current amplification, to a much larger voltage signal on output.

Input impedance The input stage with Q1 and Q3 is similar to an emitter-coupled pair (long-tailed pair), with Q2 and Q4 adding some degenerating impedance. The input impedance is relatively high because of the small current through Q1-Q4. A typical 741 op amp has an differential input impedance of about 2 MΩ. The common mode input impedance is even higher, as the input stage works at an essentially constant current.

Differential amplifier A differential voltage VI_n at the op-amp inputs (pins 3 and 2, respectively) gives rise to a small differential current in the bases of Q1 and Q2 $iI_n \approx VI_n / (2\, h_{ie} * h_{fe})$. This differential base current causes a change in the differential collector current in each leg by $iI_n * h_{fe}$. Introducing the transconductance of Q1, $gm = h_{fe} / h_{ie}$, the (small-signal) current at the base of Q15 (the input of the voltage gain stage) is $VI_n * gm / 2$.

This portion of the op amp cleverly changes a differential signal at the op amp inputs to a single-ended signal at the base of Q15, and in a way that avoids wastefully discarding the signal in either leg. To see how, notice that a small negative change in voltage at the inverting input (Q2 base) drives it out of conduction, and this incremental decrease in current passes directly from Q4 collector to its emitter, resulting in an decrease in base drive for Q15. On the other hand, a small positive change in voltage at the non-inverting input (Q1 base) drives this transistor into conduction, reflected in an increase in current at the collector of Q3. This current drives Q7 further into conduction, which turns on current mirror Q5/Q6. Thus, the increase in Q3 emitter current is mirrored in an increase in Q6 collector current, resulting also in a decrease in base drive for Q15. Besides avoiding wasting 3 dB of gain here, this technique decreases common-mode gain and feedthrough of power supply noise.

Voltage amplifier A current signal i at Q15's base gives rise to a current in Q19 of order $i * \beta^2$ (the product of the h_{fe} of each of Q15 and Q19, which are connected in a Darlington pair). This current signal develops a voltage at the bases of output transistors Q14/Q20 proportional to the h_{ie} of the respective transistor.

Output amplifier Output transistors Q14 and Q20 are each configured as an emitter follower, so no voltage gain occurs there; instead, this stage provides current gain, equal to the h_{fe} of Q14 (resp. Q20).

The output impedance is not zero, as it would be in an ideal op-amp, but with negative feedback it approaches zero at low frequencies.

Overall open-loop voltage gain The net open-loop small-signal voltage gain of the op amp involves the product of the current gain h_{fe} of some 4 transistors. In practice, the voltage gain for a typical 741-style op amp is of order 200,000, and the current gain, the ratio of input impedance (≈2–6 MΩ) to output impedance (≈50Ω) provides yet more (power) gain.

Other linear characteristics

Small-signal common mode gain The ideal op amp has infinite common-mode rejection ratio, or zero common-mode gain.

In the present circuit, if the input voltages change in the same direction, the negative feedback makes Q3/Q4 base voltage follow (with $2VBE$ below) the input voltage variations. Now the output part (Q10) of Q10-Q11 current mirror keeps up the common current through Q9/Q8 constant in spite of varying voltage. Q3/Q4 collector currents, and accordingly the output current at the base of Q15, remain unchanged.

In the typical 741 op amp, the common-mode rejection ratio is 90 dB, implying an open-loop common-mode voltage gain of about 6.

Frequency compensation The innovation of the Fairchild μA741 was the introduction of frequency compensation via an on-chip (monolithic) capacitor, simplifying application of the op amp by eliminating the need for external components for this function. The 30 pF capacitor stabilizes the amplifier via Miller compensation and functions in a manner similar to an op-amp integrator circuit. Also known as 'dominant pole compensation' because it introduces a pole that masks (dominates) the effects of other poles into the open loop frequency response; in a 741 op amp this pole can be as low as 10 Hz (where it causes a −3 dB loss of open loop voltage gain).

This internal compensation is provided to achieve unconditional stability of the amplifier in negative feedback configurations where the feedback network is non-reactive and the closed loop gain is unity or higher. By contrast, amplifiers requiring external compensation, such as the μA748, may require external compensation or closed-loop gains significantly higher than unity.

Input offset voltage The “offset null” pins may be used to place external resistors (typically in the form of the two ends of a potentiometer, with the slider connected to VS–) in parallel with the emitter resistors of Q5 and Q6, to adjust the balance of the Q5/Q6 current mirror. The potentiometer is adjusted such that the output is null (midrange) when the inputs are shorted together.

Non-linear characteristics

Input breakdown voltage The transistors Q3, Q4 help to increase the reverse VBE rating: the base-emitter junctions of the NPN transistors Q1 and Q2 break down at around 7V, but the PNP transistors Q3 and Q4 have *V*BE breakdown voltages around 50 V.[12]

Output-stage voltage swing and current limiting Variations in the quiescent current with temperature, or between parts with the same type number, are common, so crossover distortion and quiescent current may be subject to significant variation.

The output range of the amplifier is about one volt less than the supply voltage, owing in part to *V*BE of the output transistors Q14 and Q20.

The 25 Ω resistor at the Q14 emitter, along with Q17, acts to limit Q14 current to about 25 mA; otherwise, Q17 conducts no current.

Current limiting for Q20 is performed in the voltage gain stage: Q22 senses the voltage across Q19's emitter resistor (50Ω); as it turns on, it diminishes the drive current to Q15 base.

Later versions of this amplifier schematic may show a somewhat different method of output current limiting.

Applicability considerations

Note: while the 741 was historically used in audio and other sensitive equipment, such use is now rare because of the improved noise performance of more modern op-amps. Apart from generating noticeable hiss, 741s and other older op-amps may have poor common-mode rejection ratios and so will often introduce cable-borne mains hum and other common-mode interference, such as switch 'clicks', into sensitive equipment.

The "741" has come to often mean a generic op-amp IC (such as µA741, LM301, 558, LM324, TBA221 — or a more modern replacement such as the TL071). The description of the 741 output stage is qualitatively similar for many other designs (that may have quite different input stages), except:

- Some devices (µA748, LM301, LM308) are not internally compensated (require an external capacitor from output to some point within the operational amplifier, if used in low closed-loop gain applications).
- Some modern devices have "rail-to-rail output" capability, meaning that the output can range from within a few millivolts of the positive supply voltage to within a few millivolts of the negative supply voltage.

5.4.4 Classification

Op-amps may be classified by their construction:

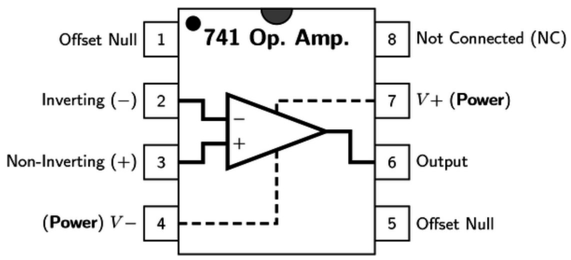
- discrete (built from individual transistors or tubes/valves)
- IC (fabricated in an Integrated circuit) — most common
- hybrid

IC op-amps may be classified in many ways, including:

- Military, Industrial, or Commercial grade (for example: the LM301 is the commercial grade version of the LM101, the LM201 is the industrial version). This may define operating temperature ranges and other environmental or quality factors.
- Classification by package type may also affect environmental hardiness, as well as manufacturing options; DIP, and other through-hole packages are tending to be replaced by surface-mount devices.
- Classification by internal compensation: op-amps may suffer from high frequency instability in some negative feedback circuits unless a small compensation capacitor modifies the phase and frequency responses. Op-amps with a built-in capacitor are termed "*compensated*", or perhaps compensated for closed-loop gains down to (say) 5. All others are considered uncompensated.
- Single, dual and quad versions of many commercial op-amp IC are available, meaning 1, 2 or 4 operational amplifiers are included in the same package.
- Rail-to-rail input (and/or output) op-amps can work with input (and/or output) signals very close to the power supply rails.
- CMOS op-amps (such as the CA3140E) provide extremely high input resistances, higher than JFET-input op-amps, which are normally higher than bipolar-input op-amps.
- other varieties of op-amp include programmable op-amps (simply meaning the quiescent current, bandwidth and so on can be adjusted by an external resistor).
- manufacturers often tabulate their op-amps according to purpose, such as low-noise pre-amplifiers, wide bandwidth amplifiers, and so on.

5.4.5 Applications

Main article: Operational amplifier applications



DIP pinout for 741-type operational amplifier

Use in electronics system design

The use of op-amps as circuit blocks is much easier and clearer than specifying all their individual circuit elements (transistors, resistors, etc.), whether the amplifiers used are integrated or discrete circuits. In the first approximation op-amps can be used as if they were ideal differential gain blocks; at a later stage limits can be placed on the acceptable range of parameters for each op-amp.

Circuit design follows the same lines for all electronic circuits. A specification is drawn up governing what the circuit is required to do, with allowable limits. For example, the gain may be required to be 100 times, with a tolerance of 5% but drift of less than 1% in a specified temperature range; the input impedance not less than one megohm; etc.

A basic circuit is designed, often with the help of circuit modeling (on a computer). Specific commercially available op-amps and other components are then chosen that meet the design criteria within the specified tolerances at acceptable cost. If not all criteria can be met, the specification may need to be modified.

A prototype is then built and tested; changes to meet or improve the specification, alter functionality, or reduce the cost, may be made.

Applications without using any feedback

That is, the op-amp is being used as a voltage comparator. Note that a device designed primarily as a comparator may be better if, for instance, speed is important or a wide range of input voltages may be found, since such devices can quickly recover from full on or full off ("saturated") states.

A *voltage level detector* can be obtained if a reference voltage V_{ref} is applied to one of the op-amp's inputs. This means that the op-amp is set up as a comparator to detect a positive voltage. If the voltage to be sensed, E_{i}, is applied to op amp's (+) input, the result is a noninverting positive-level detector: when E_{i} is above V_{ref}, VO equals $+V_{\text{sat}}$; when E_{i} is below V_{ref}, VO equals $-V_{\text{sat}}$. If E_{i} is applied to the inverting input, the circuit is an inverting positive-level detector: When E_{i} is above V_{ref}, VO equals $-V_{\text{sat}}$.

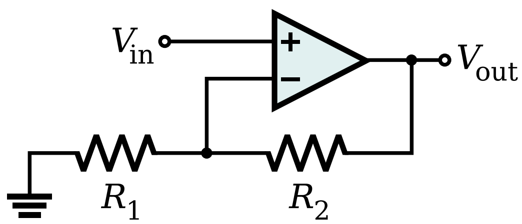
A *zero voltage level detector* ($E_{\text{i}} = 0$) can convert, for example, the output of a sine-wave from a function generator into a variable-frequency square wave. If E_{i} is a sine wave, triangular wave, or wave of any other shape that is symmetrical around zero, the zero-crossing detector's output will be square. Zero-crossing detection may also be useful in triggering TRIACs at the best time to reduce mains interference and current spikes.

Positive feedback applications

Another typical configuration of op-amps is with positive feedback, which takes a fraction of the output signal back to the non-inverting input. An important application of it is the comparator with hysteresis, the Schmitt trigger. Some circuits may use *Positive* feedback and *Negative* feedback around the same amplifier, for example Triangle wave oscillators and active filters.

Because of the wide slew-range and lack of positive feedback, the response of all the open-loop level detectors described above will be relatively slow. External overall positive feedback may be applied but (unlike internal positive feedback that may be applied within the latter stages of a purpose-designed comparator) this markedly affects the accuracy of the zero-crossing detection point. Using a general-purpose op-amp, for example, the frequency of E_{i} for the sine to square wave converter should probably be below 100 Hz.

Negative feedback applications



An op-amp connected in the non-inverting amplifier configuration

Non-inverting amplifier *In a non-inverting amplifier, the output voltage changes in the same direction as the input voltage.*

The gain equation for the op-amp is:

$$V_{\text{out}} = A_{OL}\,(V_{+} - V_{-})$$

However, in this circuit V_{-} is a function of V_{out} because of the negative feedback through the R_1 R_2 network. R_1 and R_2 form a voltage divider, and as V_{-} is a high-impedance input, it does not load it appreciably. Consequently:

$$V_- = \beta \cdot V_{\text{out}}$$

where

$$\beta = \frac{R_1}{R_1 + R_2}$$

Substituting this into the gain equation, we obtain:

$$V_{\text{out}} = A_{OL}(V_{\text{in}} - \beta \cdot V_{\text{out}})$$

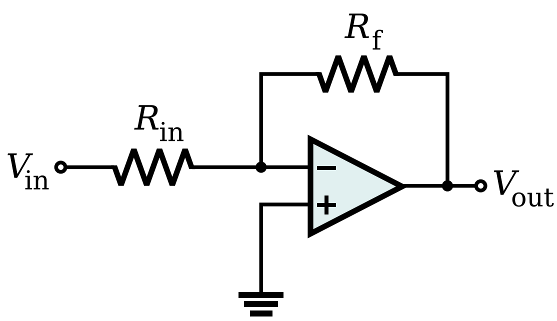
Solving for V_{out} :

$$V_{\text{out}} = V_{\text{in}} \left(\frac{1}{\beta + 1/A_{OL}} \right)$$

If A_{OL} is very large, this simplifies to

$$V_{\text{out}} \approx \frac{V_{\text{in}}}{\beta} = \frac{V_{\text{in}}}{\frac{R_1}{R_1+R_2}} = V_{\text{in}} \left(1 + \frac{R_2}{R_1} \right)$$

The non-inverting input of the operational amplifier needs a path for DC to ground; if the signal source does not supply a DC path, or if that source requires a given load impedance, then the circuit will require another resistor from the non-inverting input to ground. When the operational amplifier's input bias currents are significant, then the DC source resistances driving the inputs should be balanced.[13] The ideal value for the feedback resistors (to give minimum offset voltage) will be such that the two resistances in parallel roughly equal the resistance to ground at the non-inverting input pin. That ideal value assumes the bias currents are well-matched, which may not be true for all op-amps.[14]



An op-amp connected in the inverting amplifier configuration

Inverting amplifier *In an inverting amplifier, the output voltage changes in an opposite direction to the input voltage.*

As with the non-inverting amplifier, we start with the gain equation of the op-amp:

$$V_{\text{out}} = A_{OL}\left(V_+ - V_-\right)$$

This time, V_- is a function of both V_{out} and V_{in} due to the voltage divider formed by R_f and R_in. Again, the op-amp input does not apply an appreciable load, so:

$$V_- = \frac{1}{R_\text{f} + R_\text{in}} \left(R_\text{f} V_\text{in} + R_\text{in} V_\text{out}\right)$$

Substituting this into the gain equation and solving for V_{out} :

$$V_{\text{out}} = -V_{\text{in}} \cdot \frac{A_{OL} R_\text{f}}{R_\text{f} + R_\text{in} + A_{OL} R_\text{in}}$$

If A_{OL} is very large, this simplifies to

$$V_{\text{out}} \approx -V_{\text{in}} \frac{R_\text{f}}{R_\text{in}}$$

A resistor is often inserted between the non-inverting input and ground (so both inputs "see" similar resistances), reducing the input offset voltage due to different voltage drops due to bias current, and may reduce distortion in some op-amps.

A DC-blocking capacitor may be inserted in series with the input resistor when a frequency response down to DC is not needed and any DC voltage on the input is unwanted. That is, the capacitive component of the input impedance inserts a DC zero and a low-frequency pole that gives the circuit a bandpass or high-pass characteristic.

The potentials at the operational amplifier inputs remain virtually constant (near ground) in the inverting configuration. The constant operating potential typically results in distortion levels that are lower than those attainable with the non-inverting topology.

Other applications

- audio- and video-frequency pre-amplifiers and buffers
- differential amplifiers
- differentiators and integrators
- filters
- precision rectifiers
- precision peak detectors
- voltage and current regulators
- analog calculators

- analog-to-digital converters
- digital-to-analog converters
- Voltage clamping
- oscillators and waveform generators

Most single, dual and quad op-amps available have a standardized pin-out which permits one type to be substituted for another without wiring changes. A specific op-amp may be chosen for its open loop gain, bandwidth, noise performance, input impedance, power consumption, or a compromise between any of these factors.

5.4.6 Historical timeline

1941: A vacuum tube op-amp. An op-amp, defined as a general-purpose, DC-coupled, high gain, inverting feedback amplifier, is first found in U.S. Patent 2,401,779 “Summing Amplifier” filed by Karl D. Swartzel Jr. of Bell Labs in 1941. This design used three vacuum tubes to achieve a gain of 90 dB and operated on voltage rails of ±350 V. It had a single inverting input rather than differential inverting and non-inverting inputs, as are common in today’s op-amps. Throughout World War II, Swartzel’s design proved its value by being liberally used in the M9 artillery director designed at Bell Labs. This artillery director worked with the SCR584 radar system to achieve extraordinary hit rates (near 90%) that would not have been possible otherwise.[15]

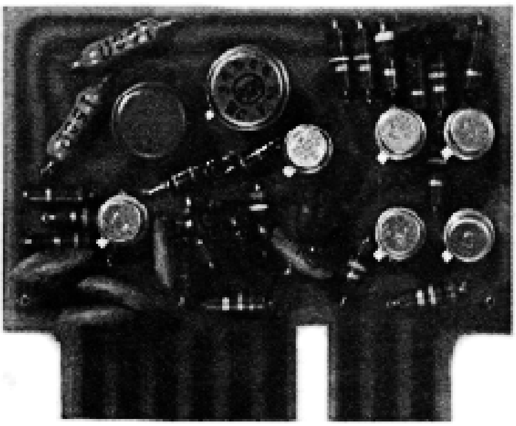
1947: An op-amp with an explicit non-inverting input. In 1947, the operational amplifier was first formally defined and named in a paper[16] by John R. Ragazzini of Columbia University. In this same paper a footnote mentioned an op-amp design by a student that would turn out to be quite significant. This op-amp, designed by Loebe Julie, was superior in a variety of ways. It had two major innovations. Its input stage used a long-tailed triode pair with loads matched to reduce drift in the output and, far more importantly, it was the first op-amp design to have two inputs (one inverting, the other non-inverting). The differential input made a whole range of new functionality possible, but it would not be used for a long time due to the rise of the chopper-stabilized amplifier.[15]

1949: A chopper-stabilized op-amp. In 1949, Edwin A. Goldberg designed a chopper-stabilized op-amp.[17] This set-up uses a normal op-amp with an additional AC amplifier that goes alongside the op-amp. The chopper gets an AC signal from DC by switching between the DC voltage and ground at a fast rate (60 Hz or 400 Hz). This signal is then amplified, rectified, filtered and fed into the op-amp’s non-inverting input. This vastly improved the gain of the op-amp while significantly reducing the output drift and DC offset. Unfortunately, any design that used a chopper couldn't use their non-inverting input for any other purpose. Nevertheless, the much improved characteristics of the chopper-stabilized op-amp made it the dominant way to use op-amps. Techniques that used the non-inverting input regularly would not be very popular until the 1960s when op-amp ICs started to show up in the field.

GAP/R’s K2-W: a vacuum-tube op-amp (1953)

1953: A commercially available op-amp. In 1953, vacuum tube op-amps became commercially available with the release of the model K2-W from George A. Philbrick Researches, Incorporated. The designation on the devices shown, GAP/R, is an acronym for the complete company name. Two nine-pin 12AX7 vacuum tubes were mounted in an octal package and had a model K2-P chopper add-on available that would effectively “use up” the non-inverting input. This op-amp was based on a descendant of Loebe Julie’s 1947 design and, along with its successors, would start the widespread use of op-amps in industry.

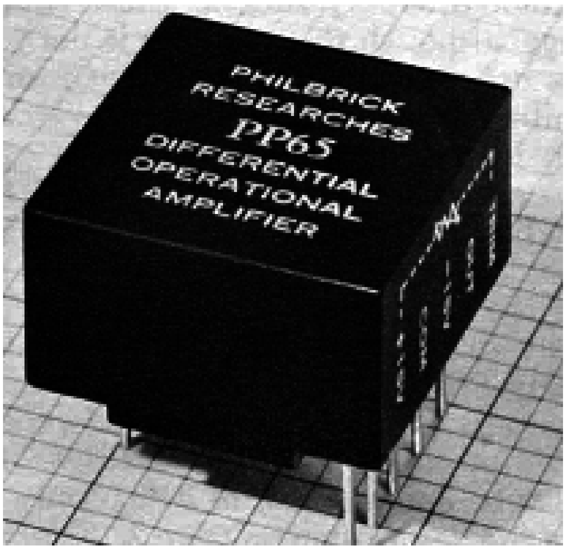
1961: A discrete IC op-amp. With the birth of the transistor in 1947, and the silicon transistor in 1954, the concept of ICs became a reality. The introduction of the



GAP/R's model P45: a solid-state, discrete op-amp (1961).

planar process in 1959 made transistors and ICs stable enough to be commercially useful. By 1961, solid-state, discrete op-amps were being produced. These op-amps were effectively small circuit boards with packages such as edge connectors. They usually had hand-selected resistors in order to improve things such as voltage offset and drift. The P45 (1961) had a gain of 94 dB and ran on ±15 V rails. It was intended to deal with signals in the range of ±10 V.

1961: A varactor bridge op-amp. There have been many different directions taken in op-amp design. Varactor bridge op-amps started to be produced in the early 1960s.[18][19] They were designed to have extremely small input current and are still amongst the best op-amps available in terms of common-mode rejection with the ability to correctly deal with hundreds of volts at their inputs.



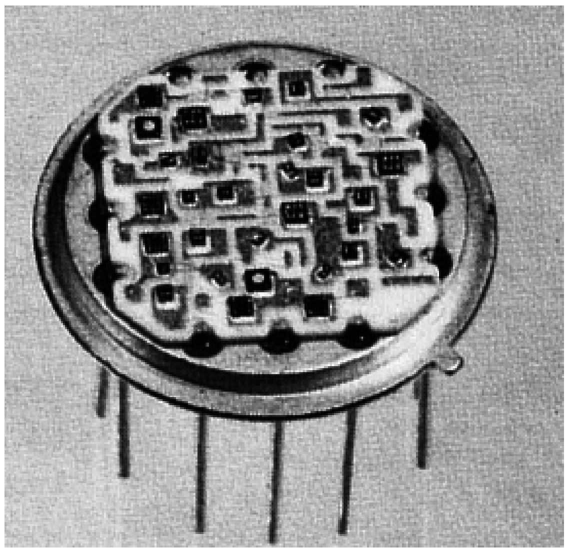
GAP/R's model PP65: a solid-state op-amp in a potted module (1962)

1962: An op-amp in a potted module. By 1962, several companies were producing modular potted packages that could be plugged into printed circuit boards. These packages were crucially important as they made the operational amplifier into a single black box which could be easily treated as a component in a larger circuit.

1963: A monolithic IC op-amp. In 1963, the first monolithic IC op-amp, the µA702 designed by Bob Widlar at Fairchild Semiconductor, was released. Monolithic ICs consist of a single chip as opposed to a chip and discrete parts (a discrete IC) or multiple chips bonded and connected on a circuit board (a hybrid IC). Almost all modern op-amps are monolithic ICs; however, this first IC did not meet with much success. Issues such as an uneven supply voltage, low gain and a small dynamic range held off the dominance of monolithic op-amps until 1965 when the µA709[20] (also designed by Bob Widlar) was released.

1968: Release of the µA741. The popularity of monolithic op-amps was further improved upon the release of the LM101 in 1967, which solved a variety of issues, and the subsequent release of the µA741 in 1968. The µA741 was extremely similar to the LM101 except that Fairchild's facilities allowed them to include a 30 pF compensation capacitor inside the chip instead of requiring external compensation. This simple difference has made the 741 *the* canonical op-amp and many modern amps base their pinout on the 741s. The µA741 is still in production, and has become ubiquitous in electronics—many manufacturers produce a version of this classic chip, recognizable by part numbers containing *741*. The same part is manufactured by several companies.

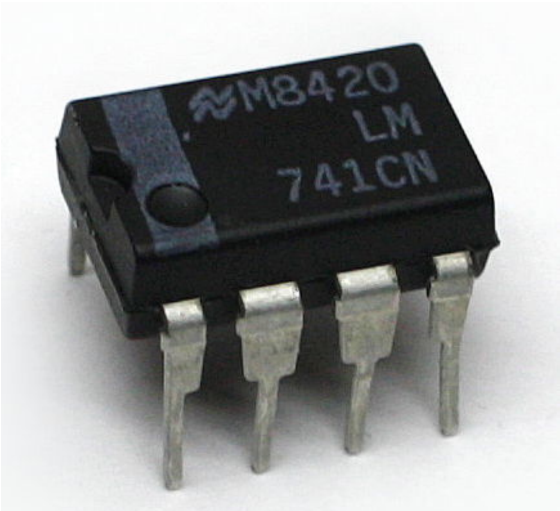
1970: First high-speed, low-input current FET design. In the 1970s high speed, low-input current designs started to be made by using FETs. These would be largely replaced by op-amps made with MOSFETs in the 1980s.



ADI's HOS-050: a high speed hybrid IC op-amp (1979)

1972: Single sided supply op-amps being produced. A single sided supply op-amp is one where the input and output voltages can be as low as the negative power supply voltage instead of needing to be at least two volts above it. The result is that it can operate in many applications with the negative supply pin on the op-amp being connected to the signal ground, thus eliminating the need for a separate negative power supply.

The LM324 (released in 1972) was one such op-amp that came in a quad package (four separate op-amps in one package) and became an industry standard. In addition to packaging multiple op-amps in a single package, the 1970s also saw the birth of op-amps in hybrid packages. These op-amps were generally improved versions of existing monolithic op-amps. As the properties of monolithic op-amps improved, the more complex hybrid ICs were quickly relegated to systems that are required to have extremely long service lives or other specialty systems.



An op-amp in a mini DIP package

Recent trends. Recently supply voltages in analog circuits have decreased (as they have in digital logic) and low-voltage op-amps have been introduced reflecting this. Supplies of 5 V and increasingly 3.3 V (sometimes as low as 1.8 V) are common. To maximize the signal range modern op-amps commonly have rail-to-rail output (the output signal can range from the lowest supply voltage to the highest) and sometimes rail-to-rail inputs.

5.4.7 See also

- Active filter
- Analog computer
- Bob Widlar
- Current conveyor
- Current-feedback operational amplifier
- Differential amplifier
- George A. Philbrick
- Instrumentation amplifier
- Negative feedback amplifier
- Op-amp swapping
- Operational amplifier applications
- Operational transconductance amplifier

5.4.8 Notes

[1] This definition hews to the convention of measuring op-amp parameters with respect to the zero voltage point in the circuit, which is usually half the total voltage between the amplifier's positive and negative power rails.

[2] Many older designs of operational amplifiers have offset null inputs to allow the offset to be manually adjusted away. Modern precision op-amps can have internal circuits that automatically cancel this offset using choppers or other circuits that measure the offset voltage periodically and subtract it from the input voltage.

[3] That the output cannot reach the power supply voltages is usually the result of limitations of the amplifier's output stage transistors. See Output stage.

[4] Widlar used this same trick in μA702 and μA709

5.4.9 References

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[10] Lu, Liang-Hung. "Electronics 2, Chapter 10" (PDF). National Taiwan University, Graduate Institute of Electronics Engineering. Retrieved 2014-02-22.

[11] Inside the ubiquitous 741 opamp; Ken Shirriff's blog.

[12] The µA741 Operational Amplifier Archived July 20, 2011, at the Wayback Machine.

[13] An input bias current of 1 µA through a DC source resistance of 10 kΩ produces a 10 mV offset voltage. If the other input bias current is the same and sees the same source resistance, then the two input offset voltages will cancel out. Balancing the DC source resistances may not be necessary if the input bias current and source resistance product is small.

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[17] http://www.analog.com/library/analogDialogue/archives/39-05/Web_ChH_final.pdf

[18] The Philbrick Archive

[19] June 1961 advertisement for Philbrick P2, http://www.philbrickarchive.org/p2%20and%206033%20ad%20rsi%20vol32%20no6%20june1961.pdf

[20] A.P. Malvino, *Electronic Principles* (2nd Ed. 1979. ISBN 0-07-039867-4) p. 476.

5.4.10 Further reading

- *Design with Operational Amplifiers and Analog Integrated Circuits*; 4th Ed; Sergio Franco; McGraw Hill; 672 pages; 2014; ISBN 978-0078028168.
- *Op Amps For Everyone*; 4th Ed; Ron Mancini; Newnes; 304 pages; 2013; ISBN 978-0123914958. (3 MB PDF of older edition)
- *Operational Amplifiers - Theory and Design*; 2nd Ed; Johan Huijsing; Springer; 430 pages; 2011; ISBN ISBN 978-9400705951. (7 MB PDF)
- *Small Signal Audio Design*; 1st Ed; Douglas Self; Focal Press; 556 pages; 2010; ISBN 978-0240521770.
- *Lessons in Electric Circuits - Volume III - Semiconductors*; 2009. (Chapter 8 is 59 pages) (4 MB PDF)
- *Linear Circuit Design Handbook*; 1st Ed; Hank Zumbahlen; Newnes; 960 pages; 2008; ISBN 978-0750687034. (35 MB PDF)
- *Op Amp Applications Handbook*; 1st Ed; Walter Jung; Newnes; 896 pages; 2004; ISBN 978-0750678445. (17 MB PDF)
- *Op Amps For Everyone*; 1st Ed; Ron Mancini; 464 pages; 2002; Texas Instruments SLOD006B. (2 MB PDF)
- *Design with Operational Amplifiers and Analog Integrated Circuits*; 3rd Ed; Sergio Franco; 672 pages; 2002; ISBN 978-0072320848.
- *Op Amps and Linear Integrated Circuits*; 1st Ed; James Fiore; Cengage Learning; 616 pages; 2000; ISBN 978-0766817937.
- *Operational Amplifiers and Linear Integrated Circuits*; 6th Ed; Robert Coughlin; Prentice Hall; 529 pages; 2000; ISBN 978-0130149916.
- *Op-Amps and Linear Integrated Circuits*; 4th Ed; Ram Gayakwad; Prentice Hall; 543 pages; 1999; ISBN 978-0132808682.
- *Basic Operational Amplifiers and Linear Integrated Circuits*; 2nd Ed; Thomas Floyd and David Buchla; Prentice Hall; 593 pages; 1998; ISBN 978-0130829870.
- *Troubleshooting Analog Circuits*; 1st Ed; Bob Pease; Newnes; 217 pages; 1991; ISBN 978-0750694995.
- *IC Op-Amp Cookbook*; 3rd Ed; Walter Jung; Prentice Hall; 433 pages; 1986; ISBN 978-0138896010.
- *Engineer's Mini-Notebook – OpAmp IC Circuits*; Forrest Mims III; Radio Shack; 49 pages; 1985; ASIN B000DZG196. (4 MB PDF)
- *Analog Applications Manual*; Signetics; 418 pages; 1979. (Chapter 3 is 32 pages) (32 MB PDF)

5.4.11 External links

- Operational Amplifiers - Chapter on All About Circuits
- Loop Gain and its Effects on Analog Circuit Performance - Introduction to loop gain, gain and phase margin, loop stability
- Simple Op Amp Measurements How to measure offset voltage, offset and bias current, gain, CMRR, and PSRR.
- Operational Amplifiers. Introductory on-line text by E. J. Mastascusa (Bucknell University).

- Introduction to op-amp circuit stages, second order filters, single op-amp bandpass filters, and a simple intercom
- *MOS op amp design: A tutorial overview*
- Operational Amplifier Noise Prediction (All Op Amps) using spot noise
- Operational Amplifier Basics
- History of the Op-amp from vacuum tubes to about 2002. Lots of detail, with schematics. IC part is somewhat ADI-centric.
- Loebe Julie historical OpAmp interview by Bob Pease
- www.PhilbrickArchive.org – A free repository of materials from George A Philbrick / Researches - Operational Amplifier Pioneer
- What's The Difference Between Operational Amplifiers And Instrumentation Amplifiers?, Electronic Design Magazine

IC Datasheets

- LM301, Single BJT OpAmp, Texas Instruments
- LM324, Quad BJT OpAmp, Texas Instruments
- LM741, Single BJT OpAmp, Texas Instruments
- NE5532, Dual BJT OpAmp, Texas Instruments (NE5534 is similar single)
- TL072, Dual JFET OpAmp, Texas Instruments (TL074 is Quad)

Chapter 6

Digital circuits

6.1 Boolean algebra

For other uses, see Boolean algebra (disambiguation).

In mathematics and mathematical logic, **Boolean algebra** is the branch of algebra in which the values of the variables are the truth values *true* and *false*, usually denoted 1 and 0 respectively. Instead of elementary algebra where the values of the variables are numbers, and the main operations are addition and multiplication, the main operations of Boolean algebra are the conjunction *and*, denoted ∧, the disjunction *or*, denoted ∨, and the negation *not*, denoted ¬. It is thus a formalism for describing logical relations in the same way that ordinary algebra describes numeric relations.

Boolean algebra was introduced by George Boole in his first book *The Mathematical Analysis of Logic* (1847), and set forth more fully in his *An Investigation of the Laws of Thought* (1854).[1] According to Huntington, the term "Boolean algebra" was first suggested by Sheffer in 1913.[2]

Boolean algebra has been fundamental in the development of digital electronics, and is provided for in all modern programming languages. It is also used in set theory and statistics.[3]

6.1.1 History

Boole's algebra predated the modern developments in abstract algebra and mathematical logic; it is however seen as connected to the origins of both fields.[4] In an abstract setting, Boolean algebra was perfected in the late 19th century by Jevons, Schröder, Huntington, and others until it reached the modern conception of an (abstract) mathematical structure.[4] For example, the empirical observation that one can manipulate expressions in the algebra of sets by translating them into expressions in Boole's algebra is explained in modern terms by saying that the algebra of sets is *a* Boolean algebra (note the indefinite article). In fact, M. H. Stone proved in 1936 that every Boolean algebra is isomorphic to a field of sets.

In the 1930s, while studying switching circuits, Claude Shannon observed that one could also apply the rules of Boole's algebra in this setting, and he introduced **switching algebra** as a way to analyze and design circuits by algebraic means in terms of logic gates. Shannon already had at his disposal the abstract mathematical apparatus, thus he cast his switching algebra as the two-element Boolean algebra. In circuit engineering settings today, there is little need to consider other Boolean algebras, thus "switching algebra" and "Boolean algebra" are often used interchangeably.[5][6][7] Efficient implementation of Boolean functions is a fundamental problem in the design of combinational logic circuits. Modern electronic design automation tools for VLSI circuits often rely on an efficient representation of Boolean functions known as (reduced ordered) binary decision diagrams (BDD) for logic synthesis and formal verification.[8]

Logic sentences that can be expressed in classical propositional calculus have an equivalent expression in Boolean algebra. Thus, **Boolean logic** is sometimes used to denote propositional calculus performed in this way.[9][10][11] Boolean algebra is not sufficient to capture logic formulas using quantifiers, like those from first order logic. Although the development of mathematical logic did not follow Boole's program, the connection between his algebra and logic was later put on firm ground in the setting of algebraic logic, which also studies the algebraic systems of many other logics.[4] The problem of determining whether the variables of a given Boolean (propositional) formula can be assigned in such a way as to make the formula evaluate to true is called the Boolean satisfiability problem (SAT), and is of importance to theoretical computer science, being the first problem shown to be NP-complete. The closely related model of computation known as a Boolean circuit relates time complexity (of an algorithm) to circuit complexity.

6.1.2 Values

Whereas in elementary algebra expressions denote mainly numbers, in Boolean algebra they denote the truth values *false* and *true*. These values are represented with the bits (or binary digits), namely 0 and 1. They do not behave like the integers 0 and 1, for which $1 + 1 = 2$, but may be identified with the elements of the two-element field

GF(2), that is, integer arithmetic modulo 2, for which 1 + 1 = 0. Addition and multiplication then play the Boolean roles of XOR (exclusive-or) and AND (conjunction) respectively, with disjunction $x \vee y$ (inclusive-or) definable as $x + y + xy$.

Boolean algebra also deals with functions which have their values in the set {0, 1}. A sequence of bits is a commonly used such function. Another common example is the subsets of a set E: to a subset F of E is associated the indicator function that takes the value 1 on F and 0 outside F. The most general example is the elements of a Boolean algebra, with all of the foregoing being instances thereof.

As with elementary algebra, the purely equational part of the theory may be developed without considering explicit values for the variables.[12]

6.1.3 Operations

Basic operations

The basic operations of Boolean calculus are as follows.

- And (conjunction), denoted $x \wedge y$ (sometimes x AND y or Kxy), satisfies $x \wedge y = 1$ if $x = y = 1$ and $x \wedge y = 0$ otherwise.
- Or (disjunction), denoted $x \vee y$ (sometimes x OR y or Axy), satisfies $x \vee y = 0$ if $x = y = 0$ and $x \vee y = 1$ otherwise.
- Not (negation), denoted $\neg x$ (sometimes NOT x, Nx or $!x$), satisfies $\neg x = 0$ if $x = 1$ and $\neg x = 1$ if $x = 0$.

If the truth values 0 and 1 are interpreted as integers, these operations may be expressed with the ordinary operations of arithmetic, or by the minimum\maximum functions:

$$x \wedge y = x \times y = min(x, y)$$
$$x \vee y = x + y - (x \times y) = max(x, y)$$
$$\neg x = 1 - x$$

Alternatively the values of $x \wedge y$, $x \vee y$, and $\neg x$ can be expressed by tabulating their values with truth tables as follows.

One may consider that only the negation and one of the two other operations are basic, because of the following identities that allow to define the conjunction in terms of the negation and the disjunction, and vice versa:

$$x \wedge y = \neg(\neg x \vee \neg y)$$
$$x \vee y = \neg(\neg x \wedge \neg y)$$

Derived operations

The three Boolean operations described above are referred to as basic, meaning that they can be taken as a basis for other Boolean operations that can be built up from them by **composition,** the manner in which operations are combined or compounded. Operations composed from the basic operations include the following examples:

$$x \to y = \neg x \vee y$$

$$x \oplus y = (x \vee y) \wedge \neg(x \wedge y)$$
$$x \equiv y = \neg(x \oplus y)$$

These definitions give rise to the following truth tables giving the values of these operations for all four possible inputs.

The first operation, $x \to y$, or Cxy, is called **material implication**. If x is true then the value of $x \to y$ is taken to be that of y. But if x is false then the value of y can be ignored; however the operation must return *some* truth value and there are only two choices, so the return value is the one that entails less, namely *true*. (Relevance logic addresses this by viewing an implication with a false premise as something other than either true or false.)

The second operation, $x \oplus y$, or Jxy, is called **exclusive or** (often abbreviated as XOR) to distinguish it from disjunction as the inclusive kind. It excludes the possibility of both x and y. Defined in terms of arithmetic it is addition mod 2 where 1 + 1 = 0.

The third operation, the complement of exclusive or, is **equivalence** or Boolean equality: $x \equiv y$, or Exy, is true just when x and y have the same value. Hence $x \oplus y$ as its complement can be understood as $x \neq y$, being true just when x and y are different. Its counterpart in arithmetic mod 2 is $x + y + 1$.

Given two operands, each with two possible values, there are $2^2 = 4$ possible combinations of inputs. Because each output can have two possible values, there are a total of $2^4 = 16$ possible binary Boolean operations.

6.1.4 Laws

A **law** of Boolean algebra is an identity such as $x \vee (y \vee z) = (x \vee y) \vee z$ between two Boolean terms, where a **Boolean term** is defined as an expression built up from variables and the constants 0 and 1 using the operations $\wedge$, $\vee$, and $\neg$. The concept can be extended to terms involving other Boolean operations such as $\oplus$, $\to$, and $\equiv$, but such extensions are unnecessary for the purposes to which the laws are put. Such purposes include the definition of a

Boolean algebra as any model of the Boolean laws, and as a means for deriving new laws from old as in the derivation of $x\vee(y\wedge z) = x\vee(z\wedge y)$ from $y\wedge z = z\wedge y$ as treated in the section on axiomatization.

Monotone laws

Boolean algebra satisfies many of the same laws as ordinary algebra when one matches up ∨ with addition and ∧ with multiplication. In particular the following laws are common to both kinds of algebra:[13]

of Associativity$\vee$	$x \vee (y \vee z) = (x \vee y) \vee z$
of Associativity$\wedge$	$x \wedge (y \wedge z) = (x \wedge y) \wedge z$
of Commutativity$\vee$	$x \vee y = y \vee x$
of Commutativity$\wedge$	$x \wedge y = y \wedge x$
of Distributivity $\wedge$ over $\vee$	$x \wedge (y \vee z) = (x \wedge y) \vee (x \wedge z)$
of Distributivity $\vee$ over $\wedge$	$x \vee (y \wedge z) = (x \vee y) \wedge (x \vee z)$
for Identity$\vee$	$x \vee 0 = x$
for Identity$\wedge$	$x \wedge 1 = x$
for Annihilator$\wedge$	$x \wedge 0 = 0$
for Annihilator$\vee$	$x \vee 1 = 1$
of Idempotence$\vee$	$x \vee x = x$
of Idempotence$\wedge$	$x \wedge x = x$
1 Absorption	$x \wedge (x \vee y) = x$
2 Absorption	$x \vee (x \wedge y) = x$

A consequence of the first of these laws is 1∨1 = 1, which is false in ordinary algebra, where 1+1 = 2. Taking x = 2 in the second law shows that it is not an ordinary algebra law either, since 2×2 = 4. The remaining four laws can be falsified in ordinary algebra by taking all variables to be 1, for example in Absorption Law 1 the left hand side is 1(1+1) = 2 while the right hand side is 1, and so on.

All of the laws treated so far have been for conjunction and disjunction. These operations have the property that changing either argument either leaves the output unchanged or the output changes in the same way as the input. Equivalently, changing any variable from 0 to 1 never results in the output changing from 1 to 0. Operations with this property are said to be **monotone**. Thus the axioms so far have all been for monotonic Boolean logic. Nonmonotonicity enters via complement ¬ as follows.[3]

Nonmonotone laws

The complement operation is defined by the following two laws.

1 Complementation	$x \wedge \neg x = 0$
2 Complementation	$x \vee \neg x = 1$

All properties of negation including the laws below follow from the above two laws alone.[3]

In both ordinary and Boolean algebra, negation works by exchanging pairs of elements, whence in both algebras it satisfies the double negation law (also called involution law)

negation Double	$\neg(\neg x) = x$

But whereas *ordinary algebra* satisfies the two laws

$$(-x)(-y) = xy$$
$$(-x) + (-y) = -(x + y)$$

Boolean algebra satisfies De Morgan's laws:

1 Morgan De	$\neg x \wedge \neg y = \neg(x \vee y)$
2 Morgan De	$\neg x \vee \neg y = \neg(x \wedge y)$

Completeness

The laws listed above define Boolean algebra, in the sense that they entail the rest of the subject. The laws *Complementation* 1 and 2, together with the monotone laws, suffice for this purpose and can therefore be taken as one possible *complete* set of laws or axiomatization of Boolean algebra. Every law of Boolean algebra follows logically from these axioms. Furthermore, Boolean algebras can then be defined as the models of these axioms as treated in the section thereon.

To clarify, writing down further laws of Boolean algebra cannot give rise to any new consequences of these axioms, nor can it rule out any model of them. In contrast, in a list of some but not all of the same laws, there could have been Boolean laws that did not follow from those on the list, and moreover there would have been models of the listed laws that were not Boolean algebras.

This axiomatization is by no means the only one, or even necessarily the most natural given that we did not pay attention to whether some of the axioms followed from others but simply chose to stop when we noticed we had enough laws, treated further in the section on axiomatizations. Or the intermediate notion of axiom can be sidestepped altogether by defining a Boolean law directly as any **tautology**, understood as an equation that holds for all values of its variables over 0 and 1. All these definitions of Boolean algebra can be shown to be equivalent.

Boolean algebra has the interesting property that $x = y$ can be proved from any non-tautology. This is because the substitution instance of any non-tautology obtained by instantiating its variables with constants 0 or 1 so as to witness its non-tautologyhood reduces by equational reasoning to 0 = 1. For example, the non-tautologyhood of

$x \wedge y = x$ is witnessed by $x = 1$ and $y = 0$ and so taking this as an axiom would allow us to infer $1 \wedge 0 = 1$ as a substitution instance of the axiom and hence $0 = 1$. We can then show $x = y$ by the reasoning $x = x \wedge 1 = x \wedge 0 = 0 = 1 = y \vee 1 = y \vee 0 = y$.

Duality principle

Principle: If {X,R} is a poset, then {X,R(inverse)} is also a poset.

There is nothing magical about the choice of symbols for the values of Boolean algebra. We could rename 0 and 1 to say α and β, and as long as we did so consistently throughout it would still be Boolean algebra, albeit with some obvious cosmetic differences.

But suppose we rename 0 and 1 to 1 and 0 respectively. Then it would still be Boolean algebra, and moreover operating on the same values. However it would not be identical to our original Boolean algebra because now we find ∨ behaving the way ∧ used to do and vice versa. So there are still some cosmetic differences to show that we've been fiddling with the notation, despite the fact that we're still using 0s and 1s.

But if in addition to interchanging the names of the values we also interchange the names of the two binary operations, *now* there is no trace of what we have done. The end product is completely indistinguishable from what we started with. We might notice that the columns for $x \wedge y$ and $x \vee y$ in the truth tables had changed places, but that switch is immaterial.

When values and operations can be paired up in a way that leaves everything important unchanged when all pairs are switched simultaneously, we call the members of each pair **dual** to each other. Thus 0 and 1 are dual, and ∧ and ∨ are dual. The **Duality Principle**, also called De Morgan duality, asserts that Boolean algebra is unchanged when all dual pairs are interchanged.

One change we did not need to make as part of this interchange was to complement. We say that complement is a **self-dual** operation. The identity or do-nothing operation x (copy the input to the output) is also self-dual. A more complicated example of a self-dual operation is $(x \wedge y) \vee (y \wedge z) \vee (z \wedge x)$. There is no self-dual binary operation that depends on both its arguments. A composition of self-dual operations is a self-dual operation. For example, if $f(x,y,z) = (x \wedge y) \vee (y \wedge z) \vee (z \wedge x)$, then $f(f(x,y,z),x,t)$ is a self-dual operation of four arguments x,y,z,t.

The principle of duality can be explained from a group theory perspective by fact that there are exactly four functions that are one-to-one mappings (automorphisms) of the set of Boolean polynomials back to itself: the identity function, the complement function, the dual function and the contradual function (complemented dual). These four functions form a group under function composition, isomorphic to the Klein four-group, acting on the set of Boolean polynomials. Walter Gottschalk remarked that consequently a more appropriate name for the phenomenon would be the *principle (or square) of quaternality*.[14]

6.1.5 Diagrammatic representations

Venn diagrams

A Venn diagram[15] is a representation of a Boolean operation using shaded overlapping regions. There is one region for each variable, all circular in the examples here. The interior and exterior of region x corresponds respectively to the values 1 (true) and 0 (false) for variable x. The shading indicates the value of the operation for each combination of regions, with dark denoting 1 and light 0 (some authors use the opposite convention).

The three Venn diagrams in the figure below represent respectively conjunction $x \wedge y$, disjunction $x \vee y$, and complement $\neg x$.

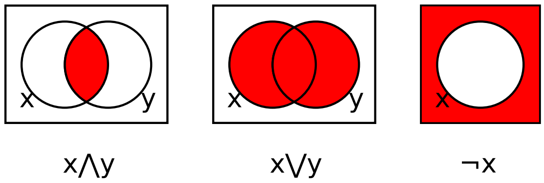

Figure 2. Venn diagrams for conjunction, disjunction, and complement

For conjunction, the region inside both circles is shaded to indicate that $x \wedge y$ is 1 when both variables are 1. The other regions are left unshaded to indicate that $x \wedge y$ is 0 for the other three combinations.

The second diagram represents disjunction $x \vee y$ by shading those regions that lie inside either or both circles. The third diagram represents complement $\neg x$ by shading the region *not* inside the circle.

While we have not shown the Venn diagrams for the constants 0 and 1, they are trivial, being respectively a white box and a dark box, neither one containing a circle. However we could put a circle for x in those boxes, in which case each would denote a function of one argument, x, which returns the same value independently of x, called a constant function. As far as their outputs are concerned, constants and constant functions are indistinguishable; the difference is that a constant takes no arguments, called a *zeroary* or *nullary* operation, while a constant function takes one argument, which it ignores, and is a *unary* operation.

Venn diagrams are helpful in visualizing laws. The commutativity laws for ∧ and ∨ can be seen from the symmetry of the diagrams: a binary operation that was not commutative would not have a symmetric diagram because interchanging x and y would have the effect of reflecting the diagram horizontally and any failure of commutativity would then appear as a failure of symmetry.

Idempotence of ∧ and ∨ can be visualized by sliding the two circles together and noting that the shaded area then becomes the whole circle, for both ∧ and ∨.

To see the first absorption law, $x \wedge (x \vee y) = x$, start with the diagram in the middle for $x \vee y$ and note that the portion of the shaded area in common with the x circle is the whole of the x circle. For the second absorption law, $x \vee (x \wedge y) = x$, start with the left diagram for $x \wedge y$ and note that shading the whole of the x circle results in just the x circle being shaded, since the previous shading was inside the x circle.

The double negation law can be seen by complementing the shading in the third diagram for $\neg x$, which shades the x circle.

To visualize the first De Morgan's law, $(\neg x) \wedge (\neg y) = \neg(x \vee y)$, start with the middle diagram for $x \vee y$ and complement its shading so that only the region outside both circles is shaded, which is what the right hand side of the law describes. The result is the same as if we shaded that region which is both outside the x circle *and* outside the y circle, i.e. the conjunction of their exteriors, which is what the left hand side of the law describes.

The second De Morgan's law, $(\neg x) \vee (\neg y) = \neg(x \wedge y)$, works the same way with the two diagrams interchanged.

The first complement law, $x \wedge \neg x = 0$, says that the interior and exterior of the x circle have no overlap. The second complement law, $x \vee \neg x = 1$, says that everything is either inside or outside the x circle.

Digital logic gates

Digital logic is the application of the Boolean algebra of 0 and 1 to electronic hardware consisting of logic gates connected to form a circuit diagram. Each gate implements a Boolean operation, and is depicted schematically by a shape indicating the operation. The shapes associated with the gates for conjunction (AND-gates), disjunction (OR-gates), and complement (inverters) are as follows.[16]

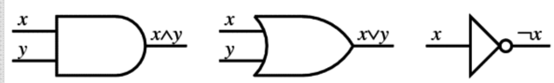

Figure 3. Logic gates

The lines on the left of each gate represent input wires or *ports*. The value of the input is represented by a voltage on the lead. For so-called "active-high" logic, 0 is represented by a voltage close to zero or "ground", while 1 is represented by a voltage close to the supply voltage; active-low reverses this. The line on the right of each gate represents the output port, which normally follows the same voltage conventions as the input ports.

Complement is implemented with an inverter gate. The triangle denotes the operation that simply copies the input to the output; the small circle on the output denotes the actual inversion complementing the input. The convention of putting such a circle on any port means that the signal passing through this port is complemented on the way through, whether it is an input or output port.

The Duality Principle, or De Morgan's laws, can be understood as asserting that complementing all three ports of an AND gate converts it to an OR gate and vice versa, as shown in Figure 4 below. Complementing both ports of an inverter however leaves the operation unchanged.

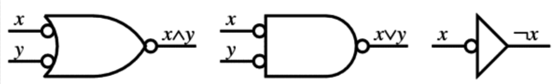

Figure 4. De Morgan equivalents

More generally one may complement any of the eight subsets of the three ports of either an AND or OR gate. The resulting sixteen possibilities give rise to only eight Boolean operations, namely those with an odd number of 1's in their truth table. There are eight such because the "odd-bit-out" can be either 0 or 1 and can go in any of four positions in the truth table. There being sixteen binary Boolean operations, this must leave eight operations with an even number of 1's in their truth tables. Two of these are the constants 0 and 1 (as binary operations that ignore both their inputs); four are the operations that depend nontrivially on exactly one of their two inputs, namely x, y, $\neg x$, and $\neg y$; and the remaining two are $x \oplus y$ (XOR) and its complement $x \equiv y$.

6.1.6 Boolean algebras

Main article: Boolean algebra (structure)

The term "algebra" denotes both a subject, namely the subject of algebra, and an object, namely an algebraic structure. Whereas the foregoing has addressed the subject of Boolean algebra, this section deals with mathematical objects called Boolean algebras, defined in full generality as any model of the Boolean laws. We begin with a special case of the notion definable without reference to the laws, namely concrete Boolean algebras, and then give the formal definition of the general notion.

Concrete Boolean algebras

A **concrete Boolean algebra** or field of sets is any nonempty set of subsets of a given set X closed under the set operations of union, intersection, and complement relative to X.[3]

(As an aside, historically X itself was required to be nonempty as well to exclude the degenerate or one-element Boolean algebra, which is the one exception to the rule that all Boolean algebras satisfy the same equations since the degenerate algebra satisfies every equation. However this exclusion conflicts with the preferred purely equational definition of "Boolean algebra," there being no way to rule out the one-element algebra using only equations— $0 \neq 1$ does not count, being a negated equation. Hence modern authors allow the degenerate Boolean algebra and let X be empty.)

Example 1. The power set 2^X of X, consisting of all subsets of X. Here X may be any set: empty, finite, infinite, or even uncountable.

Example 2. The empty set and X. This two-element algebra shows that a concrete Boolean algebra can be finite even when it consists of subsets of an infinite set. It can be seen that every field of subsets of X must contain the empty set and X. Hence no smaller example is possible, other than the degenerate algebra obtained by taking X to be empty so as to make the empty set and X coincide.

Example 3. The set of finite and cofinite sets of integers, where a cofinite set is one omitting only finitely many integers. This is clearly closed under complement, and is closed under union because the union of a cofinite set with any set is cofinite, while the union of two finite sets is finite. Intersection behaves like union with "finite" and "cofinite" interchanged.

Example 4. For a less trivial example of the point made by Example 2, consider a Venn diagram formed by n closed curves partitioning the diagram into 2^n regions, and let X be the (infinite) set of all points in the plane not on any curve but somewhere within the diagram. The interior of each region is thus an infinite subset of X, and every point in X is in exactly one region. Then the set of all 2^{2^n} possible unions of regions (including the empty set obtained as the union of the empty set of regions and X obtained as the union of all 2^n regions) is closed under union, intersection, and complement relative to X and therefore forms a concrete Boolean algebra. Again we have finitely many subsets of an infinite set forming a concrete Boolean algebra, with Example 2 arising as the case $n = 0$ of no curves.

Subsets as bit vectors

A subset Y of X can be identified with an indexed family of bits with index set X, with the bit indexed by $x \in X$ being 1 or 0 according to whether or not $x \in Y$. (This is the so-called characteristic function notion of a subset.) For example, a 32-bit computer word consists of 32 bits indexed by the set $\{0,1,2,\ldots,31\}$, with 0 and 31 indexing the low and high order bits respectively. For a smaller example, if $X = \{a,b,c\}$ where a, b, c are viewed as bit positions in that order from left to right, the eight subsets $\{\}$, $\{c\}$, $\{b\}$, $\{b,c\}$, $\{a\}$, $\{a,c\}$, $\{a,b\}$, and $\{a,b,c\}$ of X can be identified with the respective bit vectors 000, 001, 010, 011, 100, 101, 110, and 111. Bit vectors indexed by the set of natural numbers are infinite sequences of bits, while those indexed by the reals in the unit interval [0,1] are packed too densely to be able to write conventionally but nonetheless form well-defined indexed families (imagine coloring every point of the interval [0,1] either black or white independently; the black points then form an arbitrary subset of [0,1]).

From this bit vector viewpoint, a concrete Boolean algebra can be defined equivalently as a nonempty set of bit vectors all of the same length (more generally, indexed by the same set) and closed under the bit vector operations of bitwise $\wedge$, $\vee$, and $\neg$, as in $1010 \wedge 0110 = 0010$, $1010 \vee 0110 = 1110$, and $\neg 1010 = 0101$, the bit vector realizations of intersection, union, and complement respectively.

The prototypical Boolean algebra

Main article: two-element Boolean algebra

The set $\{0,1\}$ and its Boolean operations as treated above can be understood as the special case of bit vectors of length one, which by the identification of bit vectors with subsets can also be understood as the two subsets of a one-element set. We call this the **prototypical** Boolean algebra, justified by the following observation.

> The laws satisfied by all nondegenerate concrete Boolean algebras coincide with those satisfied by the prototypical Boolean algebra.

This observation is easily proved as follows. Certainly any law satisfied by all concrete Boolean algebras is satisfied by the prototypical one since it is concrete. Conversely any law that fails for some concrete Boolean algebra must have failed at a particular bit position, in which case that position by itself furnishes a one-bit counterexample to that law. Nondegeneracy ensures the existence of at least one bit position because there is only one empty bit vector.

The final goal of the next section can be understood as eliminating "concrete" from the above observation. We shall however reach that goal via the surprisingly stronger observation that, up to isomorphism, all Boolean algebras are concrete.

Boolean algebras: the definition

The Boolean algebras we have seen so far have all been concrete, consisting of bit vectors or equivalently of subsets of some set. Such a Boolean algebra consists of a set and operations on that set which can be *shown* to satisfy the laws of Boolean algebra.

Instead of showing that the Boolean laws are satisfied, we can instead postulate a set X, two binary operations on X, and one unary operation, and *require* that those operations satisfy the laws of Boolean algebra. The elements of X need not be bit vectors or subsets but can be anything at all. This leads to the more general *abstract* definition.

> A **Boolean algebra** is any set with binary operations $\wedge$ and $\vee$ and a unary operation $\neg$ thereon satisfying the Boolean laws.[17]

For the purposes of this definition it is irrelevant how the operations came to satisfy the laws, whether by fiat or proof. All concrete Boolean algebras satisfy the laws (by proof rather than fiat), whence every concrete Boolean algebra is a Boolean algebra according to our definitions. This axiomatic definition of a Boolean algebra as a set and certain operations satisfying certain laws or axioms *by fiat* is entirely analogous to the abstract definitions of group, ring, field etc. characteristic of modern or abstract algebra.

Given any complete axiomatization of Boolean algebra, such as the axioms for a complemented distributive lattice, a sufficient condition for an algebraic structure of this kind to satisfy all the Boolean laws is that it satisfy just those axioms. The following is therefore an equivalent definition.

> A **Boolean algebra** is a complemented distributive lattice.

The section on axiomatization lists other axiomatizations, any of which can be made the basis of an equivalent definition.

Representable Boolean algebras

Although every concrete Boolean algebra is a Boolean algebra, not every Boolean algebra need be concrete. Let n be a square-free positive integer, one not divisible by the square of an integer, for example 30 but not 12. The operations of greatest common divisor, least common multiple, and division into n (that is, $\neg x = n/x$), can be shown to satisfy all the Boolean laws when their arguments range over the positive divisors of n. Hence those divisors form a Boolean algebra. These divisors are not subsets of a set, making the divisors of n a Boolean algebra that is not concrete according to our definitions.

However, if we *represent* each divisor of n by the set of its prime factors, we find that this nonconcrete Boolean algebra is isomorphic to the concrete Boolean algebra consisting of all sets of prime factors of n, with union corresponding to least common multiple, intersection to greatest common divisor, and complement to division into n. So this example while not technically concrete is at least "morally" concrete via this representation, called an isomorphism. This example is an instance of the following notion.

> A Boolean algebra is called **representable** when it is isomorphic to a concrete Boolean algebra.

The obvious next question is answered positively as follows.

> Every Boolean algebra is representable.

That is, up to isomorphism, abstract and concrete Boolean algebras are the same thing. This quite nontrivial result depends on the Boolean prime ideal theorem, a choice principle slightly weaker than the axiom of choice, and is treated in more detail in the article Stone's representation theorem for Boolean algebras. This strong relationship implies a weaker result strengthening the observation in the previous subsection to the following easy consequence of representability.

> The laws satisfied by all Boolean algebras coincide with those satisfied by the prototypical Boolean algebra.

It is weaker in the sense that it does not of itself imply representability. Boolean algebras are special here, for example a relation algebra is a Boolean algebra with additional structure but it is not the case that every relation algebra is representable in the sense appropriate to relation algebras.

6.1.7 Axiomatizing Boolean algebra

Main articles: Axiomatization of Boolean algebras and Boolean algebras canonically defined

The above definition of an abstract Boolean algebra as a set and operations satisfying "the" Boolean laws raises the question, what are those laws? A simple-minded answer is "all Boolean laws," which can be defined as all equations that hold for the Boolean algebra of 0 and 1. Since there are infinitely many such laws this is not a terribly satisfactory answer in practice, leading to the next question: does it suffice to require only finitely many laws to hold?

In the case of Boolean algebras the answer is yes. In particular the finitely many equations we have listed above suffice. We say that Boolean algebra is **finitely axiomatizable** or **finitely based.**

Can this list be made shorter yet? Again the answer is yes. To begin with, some of the above laws are implied by some of the others. A sufficient subset of the above laws consists of the pairs of associativity, commutativity, and absorption laws, distributivity of $\wedge$ over $\vee$ (or the other distributivity law—one suffices), and the two complement laws. In fact this is the traditional axiomatization of Boolean algebra as a complemented distributive lattice.

By introducing additional laws not listed above it becomes possible to shorten the list yet further. In 1933 Edward Huntington showed that if the basic operations are taken to be $x \lor y$ and $\neg x$, with $x \land y$ considered a derived operation (e.g. via De Morgan's law in the form $x \land y = \neg(\neg x \lor \neg y)$), then the equation $\neg(\neg x \lor \neg y) \lor \neg(\neg x \lor y) = x$ along with the two equations expressing associativity and commutativity of $\lor$ completely axiomatized Boolean algebra. When the only basic operation is the binary NAND operation $\neg(x \land y)$, Stephen Wolfram has proposed in his book *A New Kind of Science* the single axiom $(((xy)z)(x((xz)x))) = z$ as a one-equation axiomatization of Boolean algebra, where for convenience here xy denotes the NAND rather than the AND of x and y.

6.1.8 Propositional logic

Main article: Propositional calculus

Propositional logic is a logical system that is intimately connected to Boolean algebra.[3] Many syntactic concepts of Boolean algebra carry over to propositional logic with only minor changes in notation and terminology, while the semantics of propositional logic are defined via Boolean algebras in a way that the tautologies (theorems) of propositional logic correspond to equational theorems of Boolean algebra.

Syntactically, every Boolean term corresponds to a **propositional formula** of propositional logic. In this translation between Boolean algebra and propositional logic, Boolean variables $x,y\ldots$ become **propositional variables** (or **atoms**) $P,Q,\ldots$, Boolean terms such as $x \lor y$ become propositional formulas $P \lor Q$, 0 becomes *false* or $\bot$, and 1 becomes *true* or **T**. It is convenient when referring to generic propositions to use Greek letters Φ, $\Psi,\ldots$ as metavariables (variables outside the language of propositional calculus, used when talking *about* propositional calculus) to denote propositions.

The semantics of propositional logic rely on **truth assignments**. The essential idea of a truth assignment is that the propositional variables are mapped to elements of a fixed Boolean algebra, and then the **truth value** of a propositional formula using these letters is the element of the Boolean algebra that is obtained by computing the value of the Boolean term corresponding to the formula. In classical semantics, only the two-element Boolean algebra is used, while in Boolean-valued semantics arbitrary Boolean algebras are considered. A **tautology** is a propositional formula that is assigned truth value *1* by every truth assignment of its propositional variables to an arbitrary Boolean algebra (or, equivalently, every truth assignment to the two element Boolean algebra).

These semantics permit a translation between tautologies of propositional logic and equational theorems of Boolean algebra. Every tautology Φ of propositional logic can be expressed as the Boolean equation $\Phi = 1$, which will be a theorem of Boolean algebra. Conversely every theorem $\Phi = \Psi$ of Boolean algebra corresponds to the tautologies $(\Phi \lor \neg\Psi) \land (\neg\Phi \lor \Psi)$ and $(\Phi \land \Psi) \lor (\neg\Phi \land \neg\Psi)$. If $\to$ is in the language these last tautologies can also be written as $(\Phi \to \Psi) \land (\Psi \to \Phi)$, or as two separate theorems $\Phi \to \Psi$ and $\Psi \to \Phi$; if $\equiv$ is available then the single tautology $\Phi \equiv \Psi$ can be used.

Applications

One motivating application of propositional calculus is the analysis of propositions and deductive arguments in natural language. Whereas the proposition "if $x = 3$ then $x+1 = 4$" depends on the meanings of such symbols as + and 1, the proposition "if $x = 3$ then $x = 3$" does not; it is true merely by virtue of its structure, and remains true whether "$x = 3$" is replaced by "$x = 4$" or "the moon is made of green cheese." The generic or abstract form of this tautology is "if P then P", or in the language of Boolean algebra, "$P \to P$".

Replacing P by $x = 3$ or any other proposition is called **instantiation** of P by that proposition. The result of instantiating P in an abstract proposition is called an **instance** of the proposition. Thus "$x = 3 \to x = 3$" is a tautology by virtue of being an instance of the abstract tautology "$P \to P$". All occurrences of the instantiated variable must be instantiated with the same proposition, to avoid such nonsense as $P \to x = 3$ or $x = 3 \to x = 4$.

Propositional calculus restricts attention to abstract propositions, those built up from propositional variables using Boolean operations. Instantiation is still possible within propositional calculus, but only by instantiating propositional variables by abstract propositions, such as instantiating Q by $Q \to P$ in $P \to (Q \to P)$ to yield the instance $P \to ((Q \to P) \to P)$.

(The availability of instantiation as part of the machinery of propositional calculus avoids the need for metavariables within the language of propositional calculus, since ordinary propositional variables can be considered within the language to denote arbitrary propositions. The metavariables themselves are outside the reach of instantiation, not being part of the language of propositional calculus but rather part of the same language for talking about it that this sentence is written in, where we need to be able to distinguish propositional variables and their instantiations as being distinct syntactic entities.)

Deductive systems for propositional logic

An axiomatization of propositional calculus is a set of tautologies called axioms and one or more inference rules for producing new tautologies from old. A *proof* in an axiom system A is a finite nonempty sequence of propositions each of which is either an instance of an axiom of A or follows by some rule of A from propositions appearing earlier in the proof (thereby disallowing circular reasoning). The last proposition is the **theorem** proved by the proof. Every nonempty initial segment of a proof is itself a proof, whence every proposition in a proof is itself a theorem. An axiomatization is **sound** when every theorem is a tautology, and **complete** when every tautology is a theorem.[18]

Sequent calculus

Main article: Sequent calculus

Propositional calculus is commonly organized as a Hilbert system, whose operations are just those of Boolean algebra and whose theorems are Boolean tautologies, those Boolean terms equal to the Boolean constant 1. Another form is sequent calculus, which has two sorts, propositions as in ordinary propositional calculus, and pairs of lists of propositions called sequents, such as $A\vee B$, $A\wedge C$,… $\vdash A$, $B\rightarrow C$,…. The two halves of a sequent are called the antecedent and the succedent respectively. The customary metavariable denoting an antecedent or part thereof is Γ, and for a succedent Δ; thus $\Gamma, A \vdash \Delta$ would denote a sequent whose succedent is a list Δ and whose antecedent is a list Γ with an additional proposition A appended after it. The antecedent is interpreted as the conjunction of its propositions, the succedent as the disjunction of its propositions, and the sequent itself as the entailment of the succedent by the antecedent.

Entailment differs from implication in that whereas the latter is a binary *operation* that returns a value in a Boolean algebra, the former is a binary *relation* which either holds or does not hold. In this sense entailment is an *external* form of implication, meaning external to the Boolean algebra, thinking of the reader of the sequent as also being external and interpreting and comparing antecedents and succedents in some Boolean algebra. The natural interpretation of $\vdash$ is as $\le$ in the partial order of the Boolean algebra defined by $x \le y$ just when $x\vee y = y$. This ability to mix external implication $\vdash$ and internal implication $\rightarrow$ in the one logic is among the essential differences between sequent calculus and propositional calculus.[19]

6.1.9 Applications

Boolean algebra as the calculus of two values is fundamental to computer circuits, computer programming, and mathematical logic, and is also used in other areas of mathematics such as set theory and statistics.[3]

Computers

Modern computers encode two-value Boolean logic in their circuit designs. All modern general purpose computers perform their functions using two-value Boolean logic. Their circuits are a physical manifestation of two-value Boolean logic. They achieve this in various ways: as voltages on wires in high-speed circuits and capacitive storage devices, as orientations of a magnetic domain in ferromagnetic storage devices, as holes in punched cards or paper tape, and so on. (Some early computers used decimal circuits or mechanisms instead of two-valued logic circuits.)

While it is possible to code more than two symbols in any given medium. For example, one might use respectively 0, 1, 2, and 3 volts to code a four-symbol alphabet on a wire, or holes of different sizes in a punched card. In practice however the tight constraints of high speed, small size, and low power combine to make noise a major factor. This makes it hard to distinguish between symbols when there are many of them at a single site. Rather than attempting to distinguish between four voltages on one wire, digital designers have settled on two voltages per wire, high and low. To obtain four symbols one uses two wires, and so on.

Computers use two-value Boolean circuits for the above reasons. The most common computer architectures use ordered sequences of Boolean values, called bits, of 32 or 64 values, e.g. 01101000110101100101010101001011. When programming in machine code, assembly language, and certain other programming languages, programmers work with the low-level digital structure of the data registers. These registers operate on voltages, where zero volts represents Boolean 0, and five volts represents Boolean 1. Such languages support both numeric operations and logical operations. These computers can add, subtract, multiply, divide, two sequences of bits which are interpreted as integers. These computers can perform the Boolean logical operations of disjunction, conjunction, and negation again on two sequences of bits. Programmers therefore have the option of working in and applying the laws of either numeric algebra or Boolean algebra as needed. A core differentiating feature between algebra and logic, is the carry operation with algebra but not with logic.

Two-valued logic

Other areas where two values is a good choice are the law and mathematics. In everyday relaxed conversation, nuanced or complex answers such as “maybe” or “only on the weekend” are acceptable. In more focused situations such as a court of law or theorem-based mathematics however it is deemed advantageous to frame questions so as to admit a simple yes-or-no answer—is the defendant guilty or not guilty, is the proposition true or false—and to disallow any other answer. However much of a straitjacket this might prove in practice for the respondent, the principle of the simple yes-no question has become a central feature of both judicial and mathematical logic, making two-valued logic deserving of organization and study in its own right.

A central concept of set theory is membership. Now an organization may permit multiple degrees of membership, such as novice, associate, and full. With sets however an element is either in or out. The candidates for membership in a set work just like the wires in a digital computer: each candidate is either a member or a non-member, just as each wire is either high or low.

Algebra being a fundamental tool in any area amenable to mathematical treatment, these considerations combine to make the algebra of two values of fundamental importance to computer hardware, mathematical logic, and set theory.

Two-valued logic can be extended to multi-valued logic, notably by replacing the Boolean domain $\{0, 1\}$ with the unit interval [0,1], in which case rather than only taking values 0 or 1, any value between and including 0 and 1 can be assumed. Algebraically, negation (NOT) is replaced with $1 - x$, conjunction (AND) is replaced with multiplication (xy), and disjunction (OR) is defined via De Morgan's law. Interpreting these values as logical truth values yields a multi-valued logic, which forms the basis for fuzzy logic and probabilistic logic. In these interpretations, a value is interpreted as the "degree" of truth – to what extent a proposition is true, or the probability that the proposition is true.

Boolean operations

The original application for Boolean operations was mathematical logic, where it combines the truth values, true or false, of individual formulas.

Natural languages such as English have words for several Boolean operations, in particular conjunction (*and*), disjunction (*or*), negation (*not*), and implication (*implies*). *But not* is synonymous with *and not*. When used to combine situational assertions such as "the block is on the table" and "cats drink milk," which naively are either true or false, the meanings of these logical connectives often have the meaning of their logical counterparts. However, with descriptions of behavior such as "Jim walked through the door", one starts to notice differences such as failure of commutativity, for example the conjunction of "Jim opened the door" with "Jim walked through the door" in that order is not equivalent to their conjunction in the other order, since *and* usually means *and then* in such cases. Questions can be similar: the order "Is the sky blue, and why is the sky blue?" makes more sense than the reverse order. Conjunctive commands about behavior are like behavioral assertions, as in *get dressed and go to school*. Disjunctive commands such *love me or leave me* or *fish or cut bait* tend to be asymmetric via the implication that one alternative is less preferable. Conjoined nouns such as *tea and milk* generally describe aggregation as with set union while *tea or milk* is a choice. However context can reverse these senses, as in *your choices are coffee and tea* which usually means the same as *your choices are coffee or tea* (alternatives). Double negation as in "I don't not like milk" rarely means literally "I do like milk" but rather conveys some sort of hedging, as though to imply that there is a third possibility. "Not not P" can be loosely interpreted as "surely P", and although P necessarily implies "not not P" the converse is suspect in English, much as with intuitionistic logic. In view of the highly idiosyncratic usage of conjunctions in natural languages, Boolean algebra cannot be considered a reliable framework for interpreting them.

Boolean operations are used in digital logic to combine the bits carried on individual wires, thereby interpreting them over $\{0,1\}$. When a vector of n identical binary gates are used to combine two bit vectors each of n bits, the individual bit operations can be understood collectively as a single operation on values from a Boolean algebra with 2^n elements.

Naive set theory interprets Boolean operations as acting on subsets of a given set X. As we saw earlier this behavior exactly parallels the coordinate-wise combinations of bit vectors, with the union of two sets corresponding to the disjunction of two bit vectors and so on.

The 256-element free Boolean algebra on three generators is deployed in computer displays based on raster graphics, which use bit blit to manipulate whole regions consisting of pixels, relying on Boolean operations to specify how the source region should be combined with the destination, typically with the help of a third region called the mask. Modern video cards offer all $2^{2^3} = 256$ ternary operations for this purpose, with the choice of operation being a one-byte (8-bit) parameter. The constants SRC = 0xaa or 10101010, DST = 0xcc or 11001100, and MSK = 0xf0 or 11110000 allow Boolean operations such as (SRC^DST)&MSK (meaning XOR the source and destination and then AND the result with the mask) to be written directly as a constant denoting a byte calculated at compile time, 0x60 in the (SRC^DST)&MSK example, 0x66 if just SRC^DST, etc. At run time the video card interprets the byte as the raster operation indicated by the original expression in a uniform way that requires remarkably little hardware and which takes time completely independent of the complexity of the expression.

Solid modeling systems for computer aided design offer a variety of methods for building objects from other objects, combination by Boolean operations being one of them. In this method the space in which objects exist is understood as a set S of voxels (the three-dimensional analogue of pixels in two-dimensional graphics) and shapes are defined as subsets of S, allowing objects to be combined as sets via union, intersection, etc. One obvious use is in building a complex shape from simple shapes simply as the union of the latter. Another use is in sculpting understood as removal of material: any grinding, milling, routing, or drilling operation that can be performed with physical machinery on physical materials can be simulated on the computer with the Boolean operation $x \wedge \neg y$ or $x - y$, which in set theory is set difference, remove the elements of y from those of x. Thus given two shapes one to be machined and the other the material to be removed, the result of machining the former to remove the latter is described simply as their set difference.

Boolean searches Search engine queries also employ Boolean logic. For this application, each web page on the Internet may be considered to be an "element" of a "set". The following examples use a syntax supported by Google.[20]

- Doublequotes are used to combine whitespace-separated words into a single search term.[21]
- Whitespace is used to specify logical AND, as it is the default operator for joining search terms:

"Search term 1" "Search term 2"

- The OR keyword is used for logical OR:

"Search term 1" OR "Search term 2"

- A prefixed minus sign is used for logical NOT:

"Search term 1" −"Search term 2"

6.1.10 See also

- Binary number
- Boolean algebra (structure)
- Boolean algebras canonically defined
- Booleo
- Heyting algebra
- Intuitionistic logic
- List of Boolean algebra topics
- Logic design
- Propositional calculus
- Relation algebra
- Vector logic

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[20] Not all search engines support the same query syntax. Additionally, some organizations (such as Google) provide "specialized" search engines that support alternate or extended syntax. (See e.g.,Syntax cheatsheet, Google codesearch supports regular expressions).

[21] Doublequote-delimited search terms are called "exact phrase" searches in the Google documentation.

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6.1.13 External links

- Boolean Algebra chapter on All About Circuits
- How Stuff Works – Boolean Logic
- Science and Technology - Boolean Algebra contains a list and proof of Boolean theorems and laws.

6.2 Logic gate

"Discrete logic" redirects here. For discrete circuitry, see Discrete circuit.

In electronics, a **logic gate** is an idealized or physical device implementing a Boolean function; that is, it performs a logical operation on one or more logical inputs, and produces a single logical output. Depending on the context, the term may refer to an **ideal logic gate**, one that has for instance zero rise time and unlimited fan-out, or it may refer to a non-ideal physical device[1] (see Ideal and real op-amps for comparison).

Logic gates are primarily implemented using diodes or transistors acting as electronic switches, but can also be constructed using vacuum tubes, electromagnetic relays (relay logic), fluidic logic, pneumatic logic, optics, molecules, or even mechanical elements. With amplification, logic gates can be cascaded in the same way that Boolean functions can be composed, allowing the construction of a physical model of all of Boolean logic, and therefore, all of the algorithms and mathematics that can be described with Boolean logic.

Logic circuits include such devices as multiplexers, registers, arithmetic logic units (ALUs), and computer memory, all the way up through complete microprocessors, which may contain more than 100 million gates. In modern practice, most gates are made from field-effect transistors (FETs), particularly MOSFETs (metal–oxide–semiconductor field-effect transistors).

Compound logic gates AND-OR-Invert (AOI) and OR-AND-Invert (OAI) are often employed in circuit design because their construction using MOSFETs is simpler and more efficient than the sum of the individual gates.[2]

In reversible logic, Toffoli gates are used.

6.2.1 Electronic gates

Main article: Logic family

To build a functionally complete logic system, relays, valves (vacuum tubes), or transistors can be used. The simplest family of logic gates using bipolar transistors is called resistor-transistor logic (RTL). Unlike simple diode logic gates (which do not have a gain element), RTL gates can be cascaded indefinitely to produce more complex logic functions. RTL gates were used in early integrated circuits. For higher speed and better density, the resistors used in RTL were replaced by diodes resulting in diode-transistor logic (DTL). Transistor-transistor logic (TTL) then supplanted DTL. As integrated circuits became more complex, bipolar transistors were replaced with smaller field-effect transistors (MOSFETs); see PMOS and NMOS. To reduce power consumption still further, most contemporary chip implementations of digital systems now use CMOS logic. CMOS uses complementary (both n-channel and p-channel) MOSFET devices to achieve a high speed with low power dissipation.

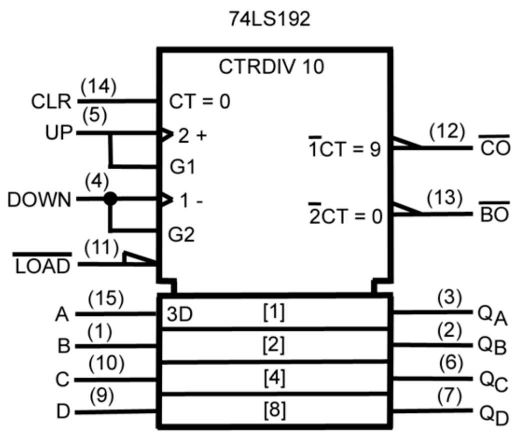
For small-scale logic, designers now use prefabricated logic gates from families of devices such as the TTL 7400 series by Texas Instruments, the CMOS 4000 series by RCA, and their more recent descendants. Increasingly, these fixed-function logic gates are being replaced by programmable logic devices, which allow designers to pack a large number of mixed logic gates into a single integrated circuit. The field-programmable nature of programmable logic devices such as FPGAs has removed the 'hard' property of hardware; it is now possible to change the logic design of a hardware system by reprogramming some of its components, thus allowing the features or function of a hardware implementation of a logic system to be changed.

Electronic logic gates differ significantly from their relay-and-switch equivalents. They are much faster, consume much less power, and are much smaller (all by a factor of a million or more in most cases). Also, there is a fundamental structural difference. The switch circuit creates a continuous metallic path for current to flow (in either direction) between its input and its output. The semiconductor logic gate, on the other hand, acts as a high-gain voltage amplifier, which sinks a tiny current at its input and produces a low-impedance voltage at its output. It is not possible for current to flow between the output and the input of a semiconductor logic gate.

Another important advantage of standardized integrated circuit logic families, such as the 7400 and 4000 families, is that they can be cascaded. This means that the output of one gate can be wired to the inputs of one or several other gates, and so on. Systems with varying degrees of complexity can be built without great concern of the designer for the internal workings of the gates, provided the limitations of each integrated circuit are considered.

The output of one gate can only drive a finite number of inputs to other gates, a number called the 'fanout limit'. Also, there is always a delay, called the 'propagation delay', from a change in input of a gate to the corresponding change in its output. When gates are cascaded, the total propagation delay is approximately the sum of the individual delays, an effect which can become a problem in high-speed circuits. Additional delay can be caused when a large number of inputs are connected to an output, due to the distributed capacitance of all the inputs and wiring and the finite amount of current that each output can provide.

6.2.2 Symbols



A synchronous 4-bit up/down decade counter symbol (74LS192) in accordance with ANSI/IEEE Std. 91-1984 and IEC Publication 60617-12.

There are two sets of symbols for elementary logic gates in common use, both defined in ANSI/IEEE Std 91-1984 and its supplement ANSI/IEEE Std 91a-1991. The “distinctive shape” set, based on traditional schematics, is used for simple drawings, and derives from MIL-STD-806 of the 1950s and 1960s. It is sometimes unofficially described as “military”, reflecting its origin. The “rectangular shape” set, based on ANSI Y32.14 and other early industry standards, as later refined by IEEE and IEC, has rectangular outlines for all types of gate and allows representation of a much wider range of devices than is possible with the traditional symbols.[3] The IEC standard, IEC 60617-12, has been adopted by other standards, such as EN 60617-12:1999 in Europe, BS EN 60617-12:1999 in the United Kingdom, and DIN EN 60617-12:1998 in Germany.

The mutual goal of IEEE Std 91-1984 and IEC 60617-

12 was to provide a uniform method of describing the complex logic functions of digital circuits with schematic symbols. These functions were more complex than simple AND and OR gates. They could be medium scale circuits such as a 4-bit counter to a large scale circuit such as a microprocessor.

IEC 617-12 and its successor IEC 60617-12 do not explicitly show the “distinctive shape” symbols, but do not prohibit them.[3] These are, however, shown in ANSI/IEEE 91 (and 91a) with this note: “The distinctive-shape symbol is, according to IEC Publication 617, Part 12, not preferred, but is not considered to be in contradiction to that standard.” IEC 60617-12 correspondingly contains the note (Section 2.1) “Although non-preferred, the use of other symbols recognized by official national standards, that is distinctive shapes in place of symbols [list of basic gates], shall not be considered to be in contradiction with this standard. Usage of these other symbols in combination to form complex symbols (for example, use as embedded symbols) is discouraged.” This compromise was reached between the respective IEEE and IEC working groups to permit the IEEE and IEC standards to be in mutual compliance with one another.

A third style of symbols was in use in Europe and is still widely used in European academia. See the column “DIN 40700” in the table in the German Wikipedia.

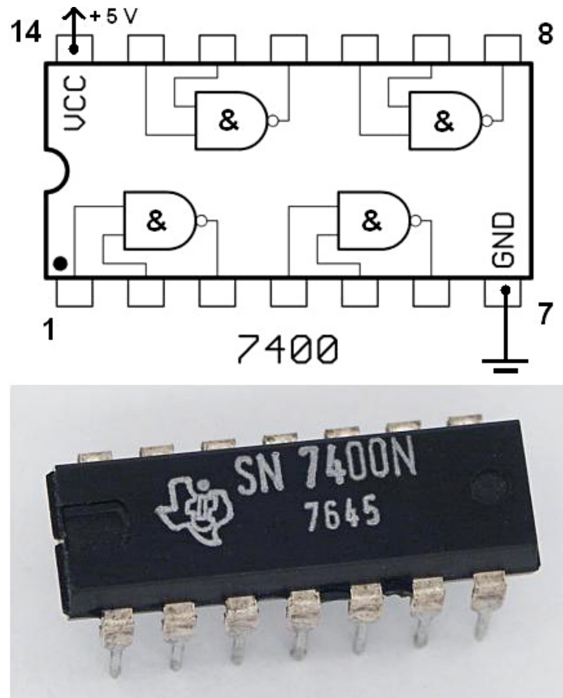
In the 1980s, schematics were the predominant method to design both circuit boards and custom ICs known as gate arrays. Today custom ICs and the field-programmable gate array are typically designed with Hardware Description Languages (HDL) such as Verilog or VHDL.

The output of two input exclusive-OR is true only when the two input values are *different*, false if they are equal, regardless of the value. If there are more than two inputs, the gate generates a true at its output if the number of trues at its input is *odd*. In practice, these gates are built from combinations of simpler logic gates.

6.2.3 Universal logic gates

For more details on the theoretical basis, see functional completeness.

Charles Sanders Peirce (winter of 1880–81) showed that NOR gates alone (or alternatively NAND gates alone) can be used to reproduce the functions of all the other logic gates, but his work on it was unpublished until 1933.[4] The first published proof was by Henry M. Sheffer in 1913, so the NAND logical operation is sometimes called Sheffer stroke; the logical NOR is sometimes called *Peirce's arrow*.[5] Consequently, these gates are sometimes called *universal logic gates*.[6]



The 7400 chip, containing four NANDs. The two additional pins supply power (+5 V) and connect the ground.

6.2.4 De Morgan equivalent symbols

By use of De Morgan's laws, an *AND* function is identical to an *OR* function with negated inputs and outputs. Likewise, an *OR* function is identical to an *AND* function with negated inputs and outputs. A NAND gate is equivalent to an OR gate with negated inputs, and a NOR gate is equivalent to an AND gate with negated inputs.

This leads to an alternative set of symbols for basic gates that use the opposite core symbol (*AND* or *OR*) but with the inputs and outputs negated. Use of these alternative symbols can make logic circuit diagrams much clearer and help to show accidental connection of an active high output to an active low input or vice versa. Any connection that has logic negations at both ends can be replaced by a negationless connection and a suitable change of gate or vice versa. Any connection that has a negation at one end and no negation at the other can be made easier to interpret by instead using the De Morgan equivalent symbol at either of the two ends. When negation or polarity indicators on both ends of a connection match, there is no logic negation in that path (effectively, bubbles “cancel”), making it easier to follow logic states from one symbol to the next. This is commonly seen in real logic diagrams - thus the reader must not get into the habit of associating the shapes exclusively as OR or AND shapes, but also take into account the bubbles at both inputs and outputs in order to determine the “true” logic function indicated.

A De Morgan symbol can show more clearly a gate's primary logical purpose and the polarity of its nodes that are considered in the “signaled” (active, on) state. Consider the simplified case where a two-input NAND gate is used to drive a motor when either of its inputs are brought low by a switch. The “signaled” state (motor on) occurs when either one OR the other switch is on. Unlike a regular NAND symbol, which suggests AND logic, the De Morgan version, a two negative-input OR gate, correctly shows that OR is of interest. The regular NAND symbol has a bubble at the output and none at the inputs (the opposite of the states that will turn the motor on), but the De Morgan symbol shows both inputs and output in the polarity that will drive the motor.

De Morgan’s theorem is most commonly used to implement logic gates as combinations of only NAND gates, or as combinations of only NOR gates, for economic reasons.

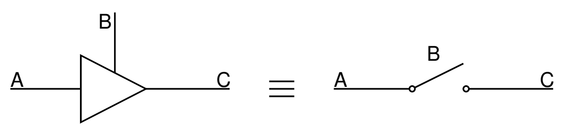
6.2.5 Data storage

Main article: Sequential logic

Logic gates can also be used to store data. A storage element can be constructed by connecting several gates in a "latch" circuit. More complicated designs that use clock signals and that change only on a rising or falling edge of the clock are called edge-triggered "flip-flops". Formally, a flip-flop is called a bistable circuit, because it has two stable states which it can maintain indefinitely. The combination of multiple flip-flops in parallel, to store a multiple-bit value, is known as a register. When using any of these gate setups the overall system has memory; it is then called a sequential logic system since its output can be influenced by its previous state(s), i.e. by the *sequence* of input states. In contrast, the output from combinatorial logic is purely a combination of its present inputs, unaffected by the previous input and output states.

These logic circuits are known as computer memory. They vary in performance, based on factors of speed, complexity, and reliability of storage, and many different types of designs are used based on the application.

6.2.6 Three-state logic gates



A tristate buffer can be thought of as a switch. If B *is on, the switch is closed. If B is off, the switch is open.*

Main article: Tri-state buffer

A three-state logic gate is a type of logic gate that can have three different outputs: high (H), low (L) and high-impedance (Z). The high-impedance state plays no role in the logic, which is strictly binary. These devices are used on buses of the CPU to allow multiple chips to send data. A group of three-states driving a line with a suitable control circuit is basically equivalent to a multiplexer, which may be physically distributed over separate devices or plug-in cards.

In electronics, a high output would mean the output is sourcing current from the positive power terminal (positive voltage). A low output would mean the output is sinking current to the negative power terminal (zero voltage). High impedance would mean that the output is effectively disconnected from the circuit.

6.2.7 History and development

The binary number system was refined by Gottfried Wilhelm Leibniz (published in 1705) and he also established that by using the binary system, the principles of arithmetic and logic could be combined. In an 1886 letter, Charles Sanders Peirce described how logical operations could be carried out by electrical switching circuits.[7] Eventually, vacuum tubes replaced relays for logic operations. Lee De Forest's modification, in 1907, of the Fleming valve can be used as an AND logic gate. Ludwig Wittgenstein introduced a version of the 16-row truth table as proposition 5.101 of *Tractatus Logico-Philosophicus* (1921). Walther Bothe, inventor of the coincidence circuit, got part of the 1954 Nobel Prize in physics, for the first modern electronic AND gate in 1924. Konrad Zuse designed and built electromechanical logic gates for his computer Z1 (from 1935–38). Claude E. Shannon introduced the use of Boolean algebra in the analysis and design of switching circuits in 1937. Active research is taking place in molecular logic gates.

6.2.8 Implementations

Main article: Unconventional computing

Since the 1990s, most logic gates are made in CMOS technology (i.e. NMOS and PMOS transistors are used). Often millions of logic gates are packaged in a single integrated circuit.

There are several logic families with different characteristics (power consumption, speed, cost, size) such as: RDL (resistor-diode logic), RTL (resistor-transistor logic), DTL (diode-transistor logic), TTL (transistor-transistor logic) and CMOS (complementary metal oxide semiconductor). There are also sub-variants, e.g. standard CMOS logic vs. advanced types using still CMOS technology, but with some optimizations for avoiding loss of speed due to slower PMOS transistors.

Non-electronic implementations are varied, though few of them are used in practical applications. Many early electromechanical digital computers, such as the Harvard

Mark I, were built from relay logic gates, using electro-mechanical relays. Logic gates can be made using pneumatic devices, such as the Sorteberg relay or mechanical logic gates, including on a molecular scale.[8] Logic gates have been made out of DNA (see DNA nanotechnology)[9] and used to create a computer called MAYA (see MAYA II). Logic gates can be made from quantum mechanical effects (though quantum computing usually diverges from boolean design). Photonic logic gates use non-linear optical effects.

In principle any method that leads to a gate that is functionally complete (for example, either a NOR or a NAND gate) can be used to make any kind of digital logic circuit. Note that the use of 3-state logic for bus systems is not needed, and can be replaced by digital multiplexers, which can be built using only simple logic gates (such as NAND gates, NOR gates, or AND and OR gates).

6.2.9 See also

- And-inverter graph
- Boolean algebra topics
- Boolean function
- Digital circuit
- Espresso heuristic logic minimizer
- Fanout
- Flip-flop (electronics)
- Functional completeness
- Karnaugh map
- Combinational logic
- Logic family
- Logical graph
- NMOS logic
- Programmable Logic Controller (PLC)
- Programmable Logic Device (PLD)
- Propositional calculus
- Quantum gate
- Race hazard
- Reversible computing
- Truth table

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[8] Mechanical Logic gates (focused on molecular scale)

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6.2.11 Further reading

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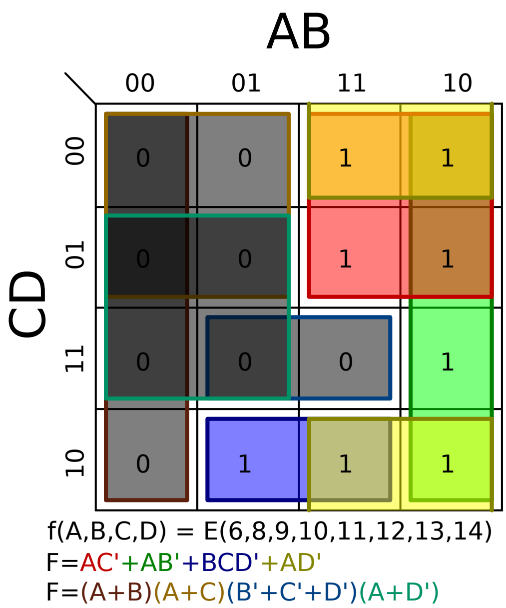
6.3 Karnaugh map

The **Karnaugh map**, also known as the **K-map**, is a method to simplify boolean algebra expressions. Maurice Karnaugh introduced it in 1953 as a refinement of Edward



An example Karnaugh map. Note that this image actually shows two Karnaugh maps: for the function f, using minterms (colored rectangles) and for its complement, using maxterms (gray rectangles). In the image, E() signifies a sum of minterms, denoted in the article as $\sum m_i$ *.*

[Veitch](#)'s 1952 **Veitch diagram**. The Karnaugh map reduces the need for extensive calculations by taking advantage of humans' pattern-recognition capability. It also permits the rapid identification and elimination of potential race conditions.

The required boolean results are transferred from a truth table onto a two-dimensional grid where the cells are ordered in Gray code, and each cell position represents one combination of input conditions, while each cell value represents the corresponding output value. Optimal groups of 1s or 0s are identified, which represent the terms of a canonical form of the logic in the original truth table.[1] These terms can be used to write a minimal boolean expression representing the required logic.

Karnaugh maps are used to simplify real-world logic requirements so that they can be implemented using a minimum number of physical logic gates. A sum-of-products expression can always be implemented using AND gates feeding into an OR gate, and a product-of-sums expression leads to OR gates feeding an AND gate.[2] Karnaugh maps can also be used to simplify logic expressions in software design. Boolean conditions, as used for example in conditional statements, can get very complicated, which makes the code difficult to read and to maintain. Once minimised, canonical sum-of-products and product-of-sums expressions can be implemented directly using AND and OR logic operators.[3]

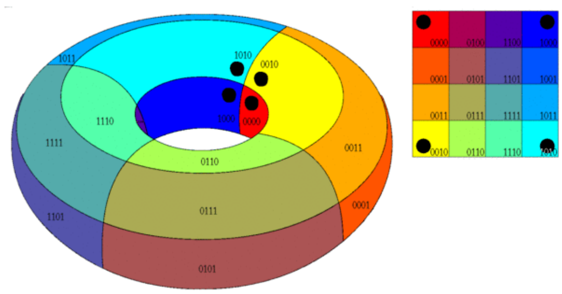
6.3.1 Example

Karnaugh maps are used to facilitate the simplification of Boolean algebra functions. Take the Boolean function described by the following truth table.

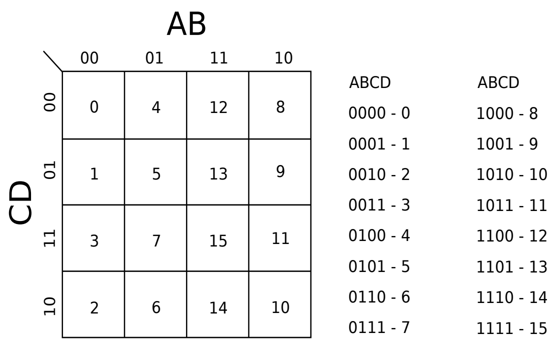
Following are two different notations describing the same function in unsimplified Boolean algebra, using the Boolean variables A , B , C , D , and their inverses.

- $f(A,B,C,D) = \sum m_i, i \in \{6,8,9,10,11,12,13,14\}$ where m_i are the minterms to map (i.e., rows that have output 1 in the truth table).
- $f(A,B,C,D) = \prod M_i, i \in \{0,1,2,3,4,5,7,15\}$ where M_i are the maxterms to map (i.e., rows that have output 0 in the truth table).

Karnaugh map



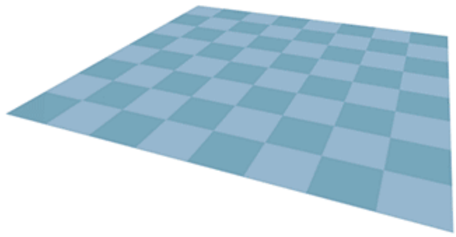
K-map drawn on a torus, and in a plane. The dot-marked cells are adjacent.



K-map construction. Instead of containing output values, this diagram shows the numbers of outputs, therefore it is not a Karnaugh map.

In the example above, the four input variables can be combined in 16 different ways, so the truth table has 16 rows, and the Karnaugh map has 16 positions. The Karnaugh map is therefore arranged in a 4 × 4 grid.

The row and column indices (shown across the top, and down the left side of the Karnaugh map) are ordered in Gray code rather than binary numerical order. Gray code



In three dimensions, one can bend a rectangle into a torus.

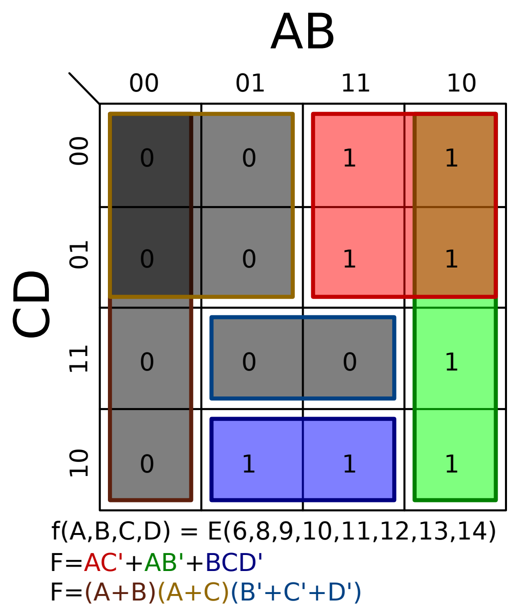


Diagram showing two K-maps. The K-map for the function f(A, B, C, D) is shown as colored rectangles which correspond to minterms. The brown region is an overlap of the red 2×2 square and the green 4×1 rectangle. The K-map for the inverse of f is shown as gray rectangles, which correspond to maxterms.

ensures that only one variable changes between each pair of adjacent cells. Each cell of the completed Karnaugh map contains a binary digit representing the function's output for that combination of inputs.

After the Karnaugh map has been constructed, it is used to find one of the simplest possible forms — a canonical form — for the information in the truth table. Adjacent 1s in the Karnaugh map represent opportunities to simplify the expression. The minterms ('minimal terms') for the final expression are found by encircling groups of 1s in the map. Minterm groups must be rectangular and must have an area that is a power of two (i.e., 1, 2, 4, 8…). Minterm rectangles should be as large as possible without containing any 0s. Groups may overlap in order to make each one larger. The optimal groupings in the example below are marked by the green, red and blue lines, and the red and green groups overlap. The red group is a 2 × 2 square, the green group is a 4 × rectangle, and the overlap area is indicated in brown.

The cells are often denoted by a shorthand which describes the logical value of the inputs that the cell covers. For example, AD would mean a cell which covers the 2x2 area where A and D are true, i.e. the cells numbered 13, 9, 15, 11 in the diagram above. On the other hand, $A\overline{D}$ would mean the cells where A is true and D is false (that is, $\overline{D}$ is true).

The grid is toroidally connected, which means that rectangular groups can wrap across the edges (see picture). Cells on the extreme right are actually 'adjacent' to those on the far left; similarly, so are those at the very top and those at the bottom. Therefore, $A\overline{D}$ can be a valid term—it includes cells 12 and 8 at the top, and wraps to the bottom to include cells 10 and 14—as is $\overline{B}\,\overline{D}$, which includes the four corners.

Solution

Once the Karnaugh map has been constructed and the adjacent 1s linked by rectangular and square boxes, the algebraic minterms can be found by examining which variables stay the same within each box.

For the red grouping:

- A is the same and is equal to 1 throughout the box, therefore it should be included in the algebraic representation of the red minterm.
- B does not maintain the same state (it shifts from 1 to 0), and should therefore be excluded.
- C does not change. It is always 0, so its complement, NOT-C, should be included. Thus, $\overline{C}$ should be included.
- D changes, so it is excluded.

Thus the first minterm in the Boolean sum-of-products expression is $A\overline{C}$.

For the green grouping, A and B maintain the same state, while C and D change. B is 0 and has to be negated before it can be included. The second term is therefore $A\overline{B}$. Note it is fine that the green grouping overlaps with the red one.

In the same way, the blue grouping gives the term $BC\overline{D}$.

The solutions of each grouping are combined: the normal form of the circuit is $A\overline{C} + A\overline{B} + BC\overline{D}$.

Thus the Karnaugh map has guided a simplification of

$$
\begin{aligned}
f(A,B,C,D) &= \overline{A}BC\overline{D} + A\overline{B}\,\overline{C}\,\overline{D} + A\overline{B}\,\overline{C}D + A\overline{B}C\overline{D} + \\
&\quad A\overline{B}CD + AB\overline{C}\,\overline{D} + AB\overline{C}D + ABC\overline{D} \\
&= A\overline{C} + A\overline{B} + BC\overline{D}
\end{aligned}
$$

It would also have been possible to derive this simplification by carefully applying the axioms of boolean algebra, but the time it takes to do that grows exponentially with the number of terms.

Inverse

The inverse of a function is solved in the same way by grouping the 0s instead.

The three terms to cover the inverse are all shown with grey boxes with different colored borders:

- brown: $\overline{A}\,\overline{B}$
- gold: $\overline{A}\,\overline{C}$
- blue: BCD

This yields the inverse:

$$\overline{f(A,B,C,D)} = \overline{A}\,\overline{B} + \overline{A}\,\overline{C} + BCD$$

Through the use of De Morgan's laws, the product of sums can be determined:

$$
\begin{aligned}
\overline{\overline{f(A,B,C,D)}} &= \overline{\overline{A}\,\overline{B} + \overline{A}\,\overline{C} + BCD} \\
f(A,B,C,D) &= \overline{\overline{A}\,\overline{B} + \overline{A}\,\overline{C} + BCD} \\
f(A,B,C,D) &= (A+B)\,(A+C)\left(\overline{B} + \overline{C} + \overline{D}\right)
\end{aligned}
$$

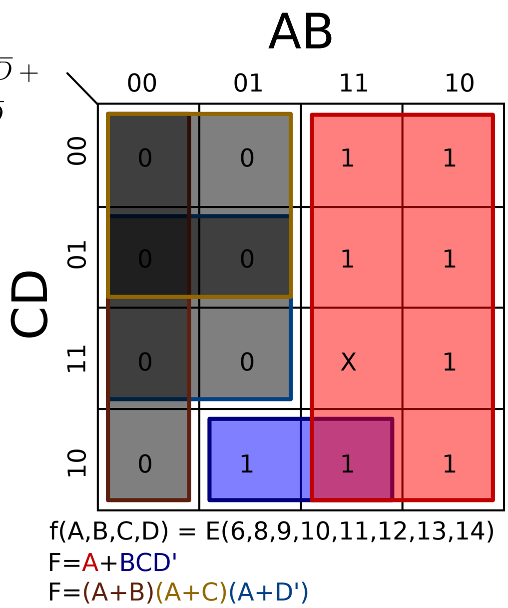
Don't cares

Karnaugh maps also allow easy minimizations of functions whose truth tables include "don't care" conditions. A “don't care” condition is a combination of inputs for which the designer doesn't care what the output is. Therefore, “don't care” conditions can either be included in or excluded from any rectangular group, whichever makes it larger. They are usually indicated on the map with a dash or X.

The example on the right is the same as the example above but with the value of *f(1,1,1,1)* replaced by a “don't care”. This allows the red term to expand all the way down and, thus, removes the green term completely.

This yields the new minimum equation:

$$f(A,B,C,D) = A + BC\overline{D}$$



The value of f(A,B,C,D) *for* ABCD = *1111 is replaced by a “don't care”. This removes the green term completely and allows the red term to be larger. It also allows blue inverse term to shift and become larger*

Note that the first term is just A , not $A\overline{C}$. In this case, the don't care has dropped a term (the green rectangle); simplified another (the red one); and removed the race hazard (removing the yellow term as shown in the following section on race hazards).

The inverse case is simplified as follows:

$$\overline{f(A,B,C,D)} = \overline{A}\,\overline{B} + \overline{A}\,\overline{C} + \overline{A}D$$

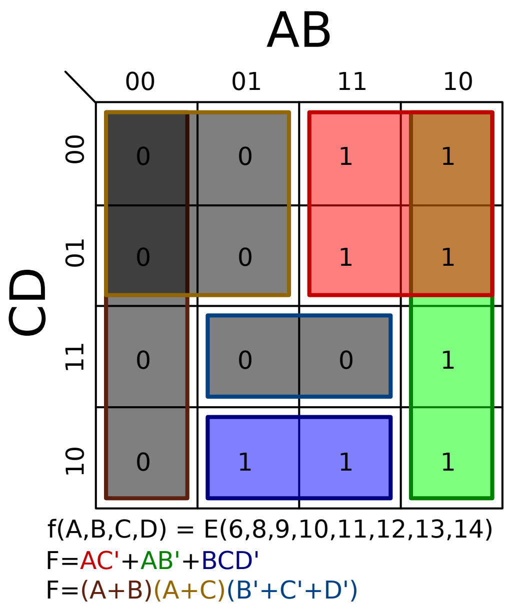
6.3.2 Race hazards

Elimination

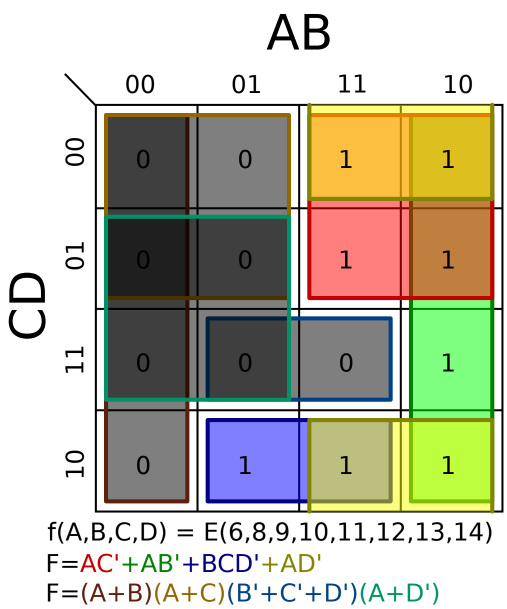
Karnaugh maps are useful for detecting and eliminating race conditions. Race hazards are very easy to spot using a Karnaugh map, because a race condition may exist when moving between any pair of adjacent, but disjoint, regions circumscribed on the map. However, because of the nature of Gray coding, *adjacent* has a special definition explained above - we're in fact moving on a torus, rather than a rectangle, wrapping around the top, bottom, and the sides.

- In the example above, a potential race condition exists when C is 1 and D is 0, A is 1, and B changes from 1 to 0 (moving from the blue state to the green state). For this case, the output is defined to remain unchanged at 1, but because this transition is not covered by a specific term in the equation, a potential for a *glitch* (a momentary transition of the output to 0) exists.

- There is a second potential glitch in the same example that is more difficult to spot: when D is 0 and A and B are both 1, with C changing from 1 to 0 (moving from the blue state to the red state). In this case the glitch wraps around from the top of the map to the bottom.



Race hazards are present in this diagram.



Above diagram with consensus terms added to avoid race hazards.

Whether glitches will actually occur depends on the physical nature of the implementation, and whether we need to worry about it depends on the application. In clocked logic, it is enough that the logic settles on the desired value in time to meet the timing deadline. In our example, we are not considering clocked logic.

In our case, an additional term of $A\overline{D}$ would eliminate the potential race hazard, bridging between the green and blue output states or blue and red output states: this is shown as the yellow region (which wraps around from the bottom to the top of the right half) in the diagram to the right.

The term is redundant in terms of the static logic of the system, but such redundant, or consensus terms, are often needed to assure race-free dynamic performance.

Similarly, an additional term of $\overline{A}D$ must be added to the inverse to eliminate another potential race hazard. Applying De Morgan's laws creates another product of sums expression for f, but with a new factor of $\left(A+\overline{D}\right)$.

2-variable map examples

The following are all the possible 2-variable, 2 × 2 Karnaugh maps. Listed with each is the minterms as a function of $\sum m()$ and the race hazard free (*see previous section*) minimum equation.

- m(0); $K = 0$
- m(1); $K = A'B'$
- m(2); $K = AB'$
- m(3); $K = A'B$
- m(4); $K = AB$
- m(1,2); $K = B'$
- m(1,3); $K = A'$
- m(1,4); $K = A'B' + AB$
- m(2,3); $K = AB' + A'B$
- m(2,4); $K = A$
- m(3,4); $K = B$
- m(1,2,3); $K = A' + B'$
- m(1,2,4); $K = A + B'$
- m(1,3,4); $K = A' + B$
- m(2,3,4); $K = A + B$
- m(1,2,3,4); $K = 1$

6.3.3 See also

- Circuit minimization
- Espresso heuristic logic minimizer
- List of boolean algebra topics
- Quine–McCluskey algorithm
- Venn diagram

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6.3.6 External links

- Quine–McCluskey algorithm implementation with a search of all solutions, by Frédéric Carpon.
- Detect Overlapping Rectangles, by Herbert Glarner.
- Using Karnaugh maps in practical applications, Circuit design project to control traffic lights.
- K-Map Tutorial for 2,3,4 and 5 variables
- Karnaugh Map Example
- POCKET–PC BOOLEAN FUNCTION SIMPLIFICATION, Ledion Bitincka — George E. Antoniou *

6.4 Finite-state machine

"State machine" redirects here. For infinite state machines, see State transition system. For fault-tolerance methodology, see State machine replication.
"SFSM" redirects here. For the Italian railway company, see Circumvesuviana.
"Finite Automata" redirects here. For the electro-industrial group, see Finite Automata (band).

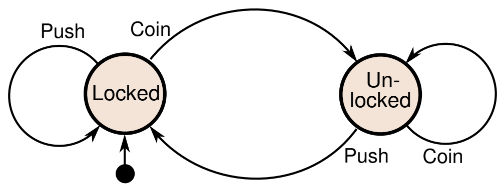
A **finite-state machine** (**FSM**) or **finite-state automaton** (plural: *automata*), or simply a **state machine**, is a mathematical model of computation used to design both computer programs and sequential logic circuits. It is conceived as an abstract machine that can be in one of a finite number of *states*. The machine is in only one state at a time; the state it is in at any given time is called the *current state*. It can change from one state to another when initiated by a triggering event or condition; this is called a *transition*. A particular FSM is defined by a list of its states, and the triggering condition for each transition.

The behavior of state machines can be observed in many devices in modern society that perform a predetermined sequence of actions depending on a sequence of events with which they are presented. Simple examples are vending machines, which dispense products when the proper combination of coins is deposited, elevators, which drop riders off at upper floors before going down, traffic lights, which change sequence when cars are waiting, and combination locks, which require the input of combination numbers in the proper order.

Finite-state machines can model a large number of problems, among which are electronic design automation, communication protocol design, language parsing and other engineering applications. In biology and artificial intelligence research, state machines or hierarchies of state machines have been used to describe neurological systems. In linguistics, they are used to describe simple parts of the grammars of natural languages.

Considered as an abstract model of computation, the finite state machine is weak; it has less computational power than some other models of computation such as the Turing machine.[1] That is, there are tasks that no FSM can do, but some Turing machines can. This is because the FSM memory is limited by the number of states.

FSMs are studied in the more general field of automata theory.



State diagram for a turnstile

A turnstile

6.4.1 Example: coin-operated turnstile

An example of a very simple mechanism that can be modeled by a state machine is a turnstile.[2][3] A turnstile, used to control access to subways and amusement park rides, is a gate with three rotating arms at waist height, one across the entryway. Initially the arms are locked, blocking the entry, preventing patrons from passing through. Depositing a coin or token in a slot on the turnstile unlocks the arms, allowing a single customer to push through. After the customer passes through, the arms are locked again until another coin is inserted.

Considered as a state machine, the turnstile has two states: ***Locked*** and ***Unlocked***.[2] There are two inputs that affect its state: putting a coin in the slot (***coin***) and pushing the arm (***push***). In the locked state, pushing on the arm has no effect; no matter how many times the input ***push*** is given, it stays in the locked state. Putting a coin in – that is, giving the machine a ***coin*** input – shifts the state from ***Locked*** to ***Unlocked***. In the unlocked state, putting additional coins in has no effect; that is, giving additional ***coin*** inputs does not change the state. However, a customer pushing through the arms, giving a ***push*** input, shifts the state back to ***Locked***.

The turnstile state machine can be represented by a state transition table, showing for each state the new state and the output (action) resulting from each input

It can also be represented by a directed graph called a state diagram *(above)*. Each of the states is represented by a node (*circle*). Edges (*arrows*) show the transitions from one state to another. Each arrow is labeled with the input that triggers that transition. Inputs that don't cause a change of state (such as a ***coin*** input in the ***Unlocked*** state) are represented by a circular arrow returning to the original state. The arrow into the ***Locked*** node from the black dot indicates it is the initial state.

6.4.2 Concepts and terminology

A *state* is a description of the status of a system that is waiting to execute a *transition*. A transition is a set of actions to be executed when a condition is fulfilled or when an event is received. For example, when using an audio system to listen to the radio (the system is in the "radio" state), receiving a "next" stimulus results in moving to the next station. When the system is in the "CD" state, the "next" stimulus results in moving to the next track. Identical stimuli trigger different actions depending on the current state.

In some finite-state machine representations, it is also possible to associate actions with a state:

- Entry action: performed *when entering* the state,
- Exit action: performed *when exiting* the state.

6.4.3 Representations

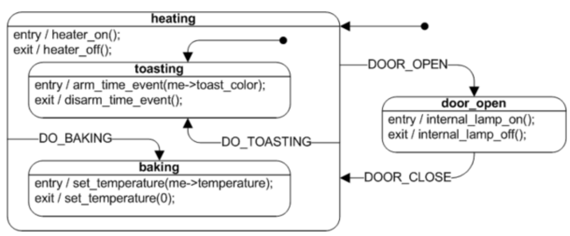


Fig. 1 UML state chart example (a toaster oven)

For an introduction, see State diagram.

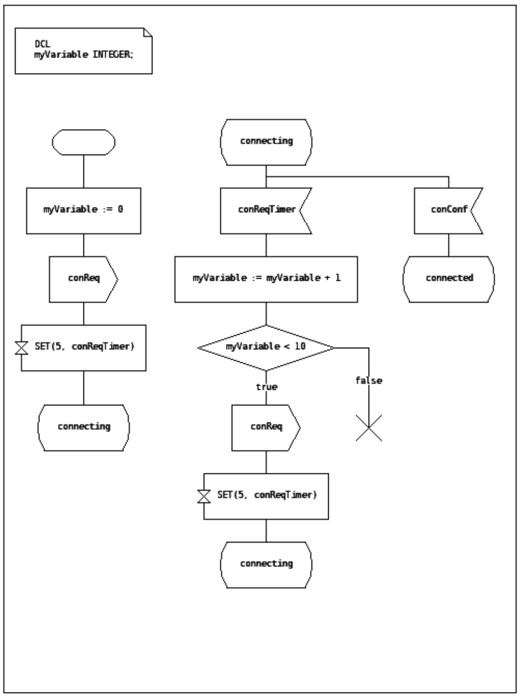


Fig. 2 SDL state machine example

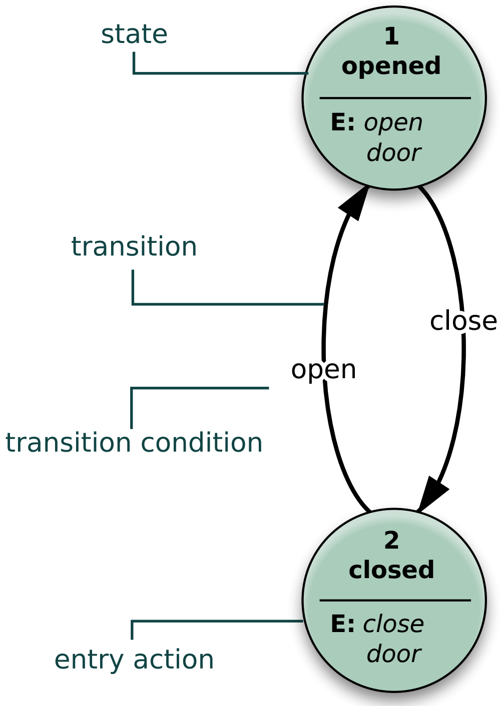


Fig. 3 Example of a simple finite state machine

State/Event table

Several state transition table types are used. The most common representation is shown below: the combination of current state (e.g. B) and input (e.g. Y) shows the next state (e.g. C). The complete action's information is not directly described in the table and can only be added using footnotes. A FSM definition including the full actions information is possible using state tables (see also virtual finite-state machine).

UML state machines

The Unified Modeling Language has a notation for describing state machines. UML state machines overcome the limitations of traditional finite state machines while retaining their main benefits. UML state machines introduce the new concepts of hierarchically nested states and orthogonal regions, while extending the notion of actions. UML state machines have the characteristics of both Mealy machines and Moore machines. They support actions that depend on both the state of the system and the triggering event, as in Mealy machines, as well as entry and exit actions, which are associated with states rather than transitions, as in Moore machines.

SDL state machines

The Specification and Description Language is a standard from ITU that includes graphical symbols to describe actions in the transition:

- send an event
- receive an event
- start a timer
- cancel a timer
- start another concurrent state machine
- decision

SDL embeds basic data types called Abstract Data Types, an action language, and an execution semantic in order to make the finite state machine executable.

Other state diagrams

There are a large number of variants to represent an FSM such as the one in figure 3.

6.4.4 Usage

In addition to their use in modeling reactive systems presented here, finite state automata are significant in many different areas, including electrical engineering, linguistics, computer science, philosophy, biology, mathematics, and logic. Finite state machines are a class of automata studied in automata theory and the theory of computation. In computer science, finite state machines are widely used in modeling of application behavior, design of hardware digital systems, software engineering, compilers, network protocols, and the study of computation and languages.

6.4.5 Classification

The state machines can be subdivided into Transducers, Acceptors, Classifiers and Sequencers.[4]

Acceptors and recognizers

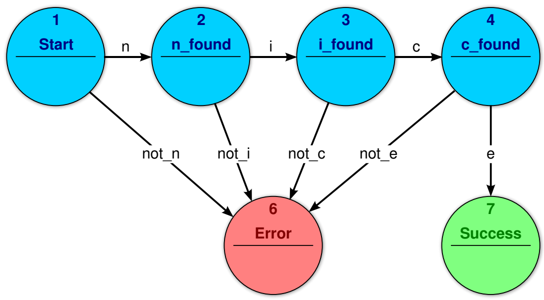


Fig. 4 Acceptor FSM: parsing the string "nice"

Acceptors (also called **recognizers** and **sequence detectors**) produce binary output, indicating whether or not received input is accepted. Each state of an FSM is either "accepting" or "not accepting". Once all input has been received, if the current state is an accepting state, the input is accepted; otherwise it is rejected. As a rule, input is a series of symbols (characters); actions are not used. The example in figure 4 shows a finite state machine that accepts the string "nice". In this FSM, the only accepting state is state 7.

A machine could also be described as defining a language, that would contain every string accepted by the machine but none of the rejected ones; that language is "accepted" by the machine. By definition, the languages accepted by FSMs are the regular languages—; a language is regular if there is some FSM that accepts it.

The problem of determining the language accepted by a given FSA is an instance of the algebraic path problem—itself a generalization of the shortest path problem to graphs with edges weighted by the elements of an (arbitrary) semiring.[5][6][7]

Start state The start state is usually shown drawn with an arrow "pointing at it from any where" (Sipser (2006) p. 34).

Accept (or final) states **Accept states** (also referred to as **accepting** or **final** states) are those at which the machine reports that the input string, as processed so far, is a member of the language it accepts. Accepting states are usually represented by double circles.

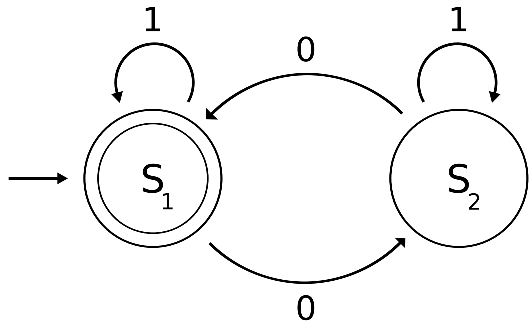


*Fig. 5: Representation of a finite-state machine; this example shows one that determines whether a binary number has an even number of 0s, where S_1 is an **accepting state**.*

The start state can also be an accepting state, in which case the automaton accepts the empty string. If the start state is not an accepting state and there are no connecting edges to any of the accepting states, then the automaton is accepting nothing.

An example of an accepting state appears in Fig.5: a deterministic finite automaton (DFA) that detects whether the binary input string contains an even number of 0s.

S_1 (which is also the start state) indicates the state at which an even number of 0s has been input. S_1 is therefore an accepting state. This machine will finish in an accept state, if the binary string contains an even number of 0s (including any binary string containing no 0s). Examples of strings accepted by this DFA are ε (the empty string), 1, 11, 11…, 00, 010, 1010, 10110, etc…

Classifier is a generalization that, similar to acceptor, produces single output when terminates but has more than two terminal states.

Transducers

Main article: Finite state transducer

Transducers generate output based on a given input and/or a state using actions. They are used for control applications and in the field of computational linguistics.

In control applications, two types are distinguished:

Moore machine The FSM uses only entry actions, i.e., output depends only on the state. The advantage of the Moore model is a simplification of the behaviour. Consider an elevator door. The state machine recognizes two commands: "command_open" and "command_close", which trigger state changes. The entry action (E:) in state "Opening" starts a mo-

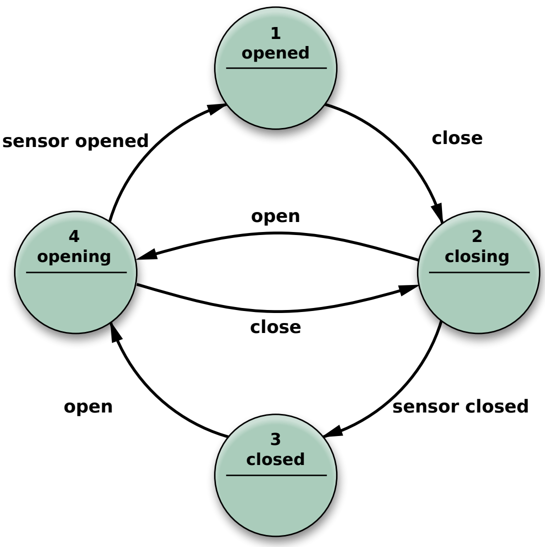


Fig. 6 Transducer FSM: Moore model example

tor opening the door, the entry action in state "Closing" starts a motor in the other direction closing the door. States "Opened" and "Closed" stop the motor when fully opened or closed. They signal to the outside world (e.g., to other state machines) the situation: "door is open" or "door is closed".

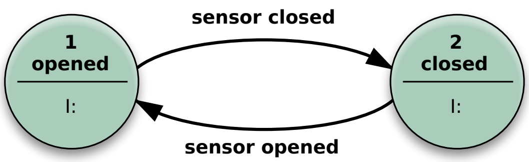


Fig. 7 Transducer FSM: Mealy model example

Mealy machine The FSM uses only input actions, i.e., output depends on input and state. The use of a Mealy FSM leads often to a reduction of the number of states. The example in figure 7 shows a Mealy FSM implementing the same behaviour as in the Moore example (the behaviour depends on the implemented FSM execution model and will work, e.g., for virtual FSM but not for event driven FSM). There are two input actions (I:): "start motor to close the door if command_close arrives" and "start motor in the other direction to open the door if command_open arrives". The "opening" and "closing" intermediate states are not shown.

Generators

The **sequencers** or **generators** are a subclass of aforementioned types that have a single-letter input alphabet. They produce only one sequence, which can be interpreted as output sequence of transducer or classifier outputs.

Determinism

A further distinction is between **deterministic** (DFA) and **non-deterministic** (NFA, GNFA) automata. In deterministic automata, every state has exactly one transition for each possible input. In non-deterministic automata, an input can lead to one, more than one or no transition for a given state. This distinction is relevant in practice, but not in theory, as there exists an algorithm (the powerset construction) that can transform any NFA into a more complex DFA with identical functionality.

The FSM with only one state is called a combinatorial FSM and uses only input actions. This concept is useful in cases where a number of FSM are required to work together, and where it is convenient to consider a purely combinatorial part as a form of FSM to suit the design tools.[8]

6.4.6 Alternative semantics

There are other sets of semantics available to represent state machines. For example, there are tools for modeling and designing logic for embedded controllers.[9] They combine hierarchical state machines, flow graphs, and truth tables into one language, resulting in a different formalism and set of semantics.[10] Figure 8 illustrates this mix of state machines and flow graphs with a set of states to represent the state of a stopwatch and a flow graph to control the ticks of the watch. These charts, like Harel's original state machines,[11] support hierarchically nested states, orthogonal regions, state actions, and transition actions.[12]

6.4.7 FSM logic

The next state and output of an FSM is a function of the input and of the current state. The FSM logic is shown in Figure 8.

6.4.8 Mathematical model

In accordance with the general classification, the following formal definitions are found:

- A *deterministic finite state machine* or *acceptor deterministic finite state machine* is a quintuple $(\Sigma, S, s_0, \delta, F)$, where:
  - Σ is the input alphabet (a finite, non-empty set of symbols).
  - S is a finite, non-empty set of states.

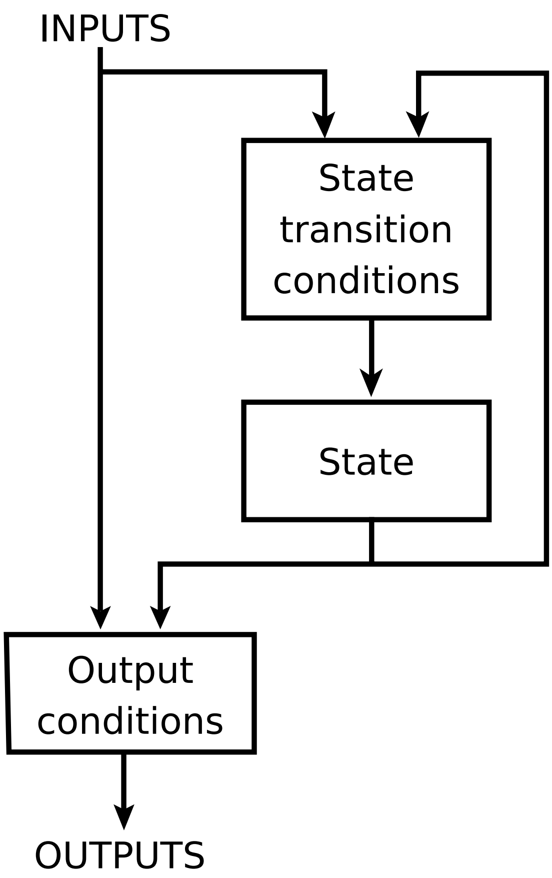


Fig. 8 FSM Logic (Mealy)

- s_0 is an initial state, an element of S .
- δ is the state-transition function: $\delta : S \times \Sigma \rightarrow S$ (in a nondeterministic finite automaton it would be $\delta : S \times \Sigma \rightarrow \mathcal{P}(S)$, i.e., δ would return a set of states).
- F is the set of final states, a (possibly empty) subset of S .

For both deterministic and non-deterministic FSMs, it is conventional to allow δ to be a partial function, i.e. $\delta(q, x)$ does not have to be defined for every combination of $q \in S$ and $x \in \Sigma$. If an FSM M is in a state q , the next symbol is x and $\delta(q, x)$ is not defined, then M can announce an error (i.e. reject the input). This is useful in definitions of general state machines, but less useful when transforming the machine. Some algorithms in their default form may require total functions.

A finite-state machine is a restricted Turing machine where the head can only perform "read" operations, and always moves from left to right.[13]

- A *finite state transducer* is a sextuple $(\Sigma, \Gamma, S, s_0, \delta, \omega)$, where:
  - Σ is the input alphabet (a finite non-empty set of symbols).
  - Γ is the output alphabet (a finite, non-empty set of symbols).
  - S is a finite, non-empty set of states.
  - s_0 is the initial state, an element of S . In a nondeterministic finite automaton, s_0 is a set of initial states.
  - δ is the state-transition function: $\delta : S \times \Sigma \rightarrow S$.
  - ω is the output function.

If the output function is a function of a state and input alphabet ($\omega : S \times \Sigma \rightarrow \Gamma$) that definition corresponds to the **Mealy model**, and can be modelled as a Mealy machine. If the output function depends only on a state ($\omega : S \rightarrow \Gamma$) that definition corresponds to the **Moore model**, and can be modelled as a Moore machine. A finite-state machine with no output function at all is known as a semiautomaton or transition system.

If we disregard the first output symbol of a Moore machine, $\omega(s_0)$, then it can be readily converted to an output-equivalent Mealy machine by setting the output function of every Mealy transition (i.e. labeling every edge) with the output symbol given of the destination Moore state. The converse transformation is less straightforward because a Mealy machine state may have different output labels on its incoming transitions (edges). Every such state needs to be split in multiple Moore machine states, one for every incident output symbol.[14]

6.4.9 Optimization

Main article: DFA minimization

Optimizing an FSM means finding the machine with the minimum number of states that performs the same function. The fastest known algorithm doing this is the Hopcroft minimization algorithm.[15][16] Other techniques include using an implication table, or the Moore reduction procedure. Additionally, acyclic FSAs can be minimized in linear time.[17]

6.4.10 Implementation

Hardware applications

In a digital circuit, an FSM may be built using a programmable logic device, a programmable logic controller, logic gates and flip flops or relays. More specifically, a hardware implementation requires a register to store state variables, a block of combinational logic that determines the state transition, and a second block of combinational logic that determines the output of an FSM. One of the classic hardware implementations is the Richards controller.

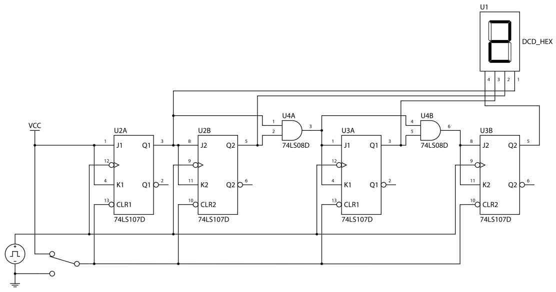


Fig. 9 The circuit diagram for a 4-bit TTL counter, a type of state machine

A particular case of Moore FSM, when output is directly connected to the state flip-flops, that is when output function is simple identity, is known as Medvedev FSM.[18] It is advised in chip design that no logic is placed between primary I/O and registers to minimize interchip delays, which are usually long and limit the FSM frequencies.

Through state encoding for low power state machines may be optimized to minimize power consumption.

Software applications

The following concepts are commonly used to build software applications with finite state machines:

- Automata-based programming
- Event-driven FSM
- Virtual FSM (VFSM)
- State design pattern

Finite automata and compilers

Finite automata are often used in the frontend of programming language compilers. Such a frontend may comprise several finite state machines that implement a lexical analyzer and a parser. Starting from a sequence of characters, the lexical analyzer builds a sequence of language tokens (such as reserved words, literals, and identifiers) from which the parser builds a syntax tree. The lexical analyzer and the parser handle the regular and context-free parts of the programming language's grammar.[19]

6.4.11 See also

- Abstract state machines (ASM)
- Artificial intelligence (AI)
- Abstract State Machine Language (AsmL)
- Behavior model
- Communicating finite-state machine
- Control system
- Control table
- Decision tables
- DEVS: Discrete Event System Specification
- Extended finite-state machine (EFSM)
- Finite state machine with datapath
- Hidden Markov model
- Petri net
- Pushdown automaton
- Quantum finite automata (QFA)
- Recognizable language
- Sequential logic
- Specification and Description Language
- State diagram
- State pattern
- SCXML
- Transition system
- Tree automaton
- Turing machine
- UML state machine
- YAKINDU Statechart Tools

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Finite Markov chain processes

> "We may think of a Markov chain as a process that moves successively through a set of states s_1, s_2, …, *sr*. … if it is in state *si* it moves on to the next stop to state *sj* with probability *pij*. These probabilities can be exhibited in the form of a transition matrix" (Kemeny (1959), p. 384)

Finite Markov-chain processes are also known as subshifts of finite type.

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6.4.14 External links

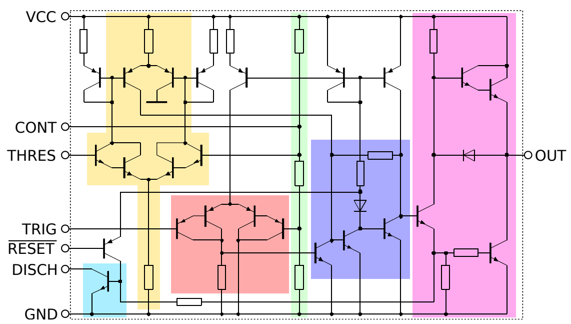
- Finite State Automata at DMOZ
- *Modeling a Simple AI behavior using a Finite State Machine* Example of usage in Video Games
- Free On-Line Dictionary of Computing description of Finite State Machines
- NIST Dictionary of Algorithms and Data Structures description of Finite State Machines
- Interactive FSM: Control Circuit, demonstrates the logic flow of the Finite State Machines.
- FSM simulator, simulates DFAs, NFAs and ε-NFAs, including generated by regular expression.

6.5 555 timer IC

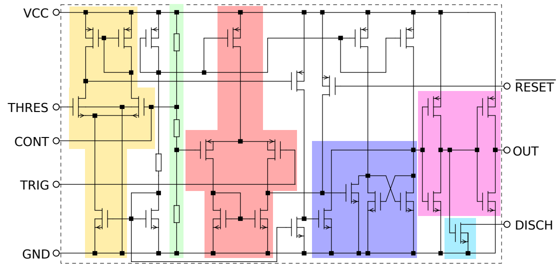
The **555 timer IC** is an integrated circuit (chip) used in a variety of timer, pulse generation, and oscillator applications. The 555 can be used to provide time delays, as an oscillator, and as a flip-flop element. Derivatives provide up to four timing circuits in one package.

Introduced in 1971 by American company Signetics, the 555 is still in widespread use due to its low price, ease of use, and stability. It is now made by many companies in the original bipolar and also in low-power CMOS types. As of 2003, it was estimated that 1 billion units are manufactured every year.[1]

6.5.1 Design



Internal schematic (bipolar version)



Internal schematic (CMOS version)

The IC was designed in 1971 by Hans R. Camenzind under contract to Signetics, which was later acquired by Dutch company Philips Semiconductors (now NXP).

Depending on the manufacturer, the standard 555 package includes 25 transistors, 2 diodes and 15 resistors on a silicon chip installed in an 8-pin mini dual-in-line package (DIP-8).[2] Variants available include the 556 (a 14-pin DIP combining two 555s on one chip), and the two 558 & 559s (both a 16-pin DIP combining four slightly modified 555s with DIS & THR connected internally, and TR is falling edge sensitive instead of level sensitive).

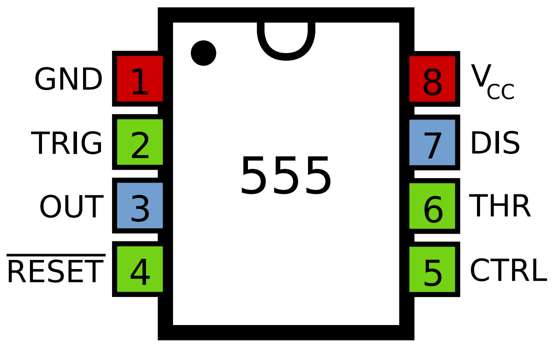
The **NE555** parts were commercial temperature range, 0 °C to +70 °C, and the **SE555** part number designated the military temperature range, −55 °C to +125 °C. These were available in both high-reliability metal can (T package) and inexpensive epoxy plastic (V package) packages. Thus the full part numbers were NE555V, NE555T, SE555V, and SE555T. It has been hypothesized that the 555 got its name from the three 5 kΩ resistors used within,[3] but Hans Camenzind has stated that the number was arbitrary.[1]

Low-power versions of the 555 are also available, such as the 7555 and CMOS TLC555.[4] The 7555 is designed to cause less supply noise than the classic 555 and the manufacturer claims that it usually does not require a "control" capacitor and in many cases does not require a decoupling capacitor on the power supply. Those parts should generally be included, however, because noise produced by the timer or variation in power supply voltage might interfere with other parts of a circuit or influence its threshold voltages.

Pins

The connection of the pins for a DIP package is as follows:

Pin 5 is also sometimes called the CONTROL VOLTAGE pin. By applying a voltage to the CONTROL VOLTAGE input one can alter the timing characteristics of the device. In most applications, the CONTROL VOLTAGE input is not used. It is usual to connect a 10 nF capacitor between pin 5 and 0 V to prevent interference. The CONTROL VOLTAGE input can be used to build an astable multivibrator with a frequency-



Pinout diagram

modulated output.

Modes

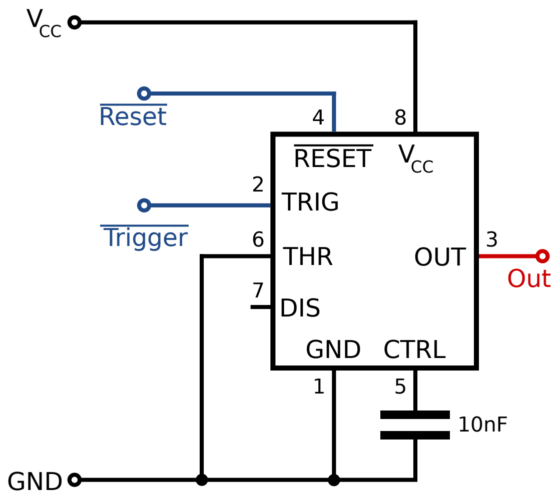
The IC 555 has three operating modes:

1. **Bistable** mode or Schmitt trigger – the 555 can operate as a flip-flop, if the DIS pin is not connected and no capacitor is used. Uses include bounce-free latched switches.

2. **Monostable** mode – in this mode, the 555 functions as a “one-shot” pulse generator. Applications include timers, missing pulse detection, bounce-free switches, touch switches, frequency divider, capacitance measurement, pulse-width modulation (PWM) and so on.

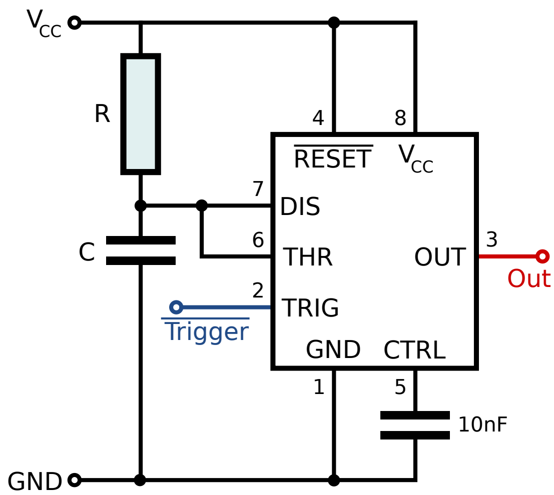
3. **Astable** (free-running) mode – the 555 can operate as an electronic oscillator. Uses include LED and lamp flashers, pulse generation, logic clocks, tone generation, security alarms, pulse position modulation and so on. The 555 can be used as a simple ADC, converting an analog value to a pulse length (e.g., selecting a thermistor as timing resistor allows the use of the 555 in a temperature sensor and the period of the output pulse is determined by the temperature). The use of a microprocessor-based circuit can then convert the pulse period to temperature, linearize it and even provide calibration means.

Bistable In bistable (also called Schmitt trigger) mode, the 555 timer acts as a basic flip-flop. The trigger and reset inputs (pins 2 and 4 respectively on a 555) are held high via pull-up resistors while the threshold input (pin 6) is simply floating. Thus configured, pulling the trigger momentarily to ground acts as a 'set' and transitions the output pin (pin 3) to Vcc (high state). Pulling the reset input to ground acts as a 'reset' and transitions the output pin to ground (low state). No timing capacitors are required in a bistable configuration. Pin 5 (control voltage) is connected to ground via a small-value capacitor (usually 0.01 to 0.1 µF). Pin 7 (discharge) is left floating.[5]



Schematic of a 555 in bistable mode

Monostable See also: RC circuit
The output pulse ends when the voltage on the capacitor



Schematic of a 555 in monostable mode

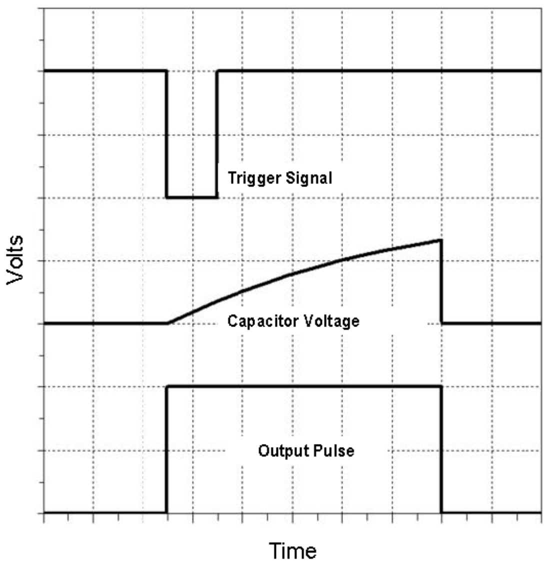
equals 2/3 of the supply voltage. The output pulse width can be lengthened or shortened to the need of the specific application by adjusting the values of R and C.[6]

The output pulse width of time *t*, which is the time it takes to charge C to 2/3 of the supply voltage, is given by

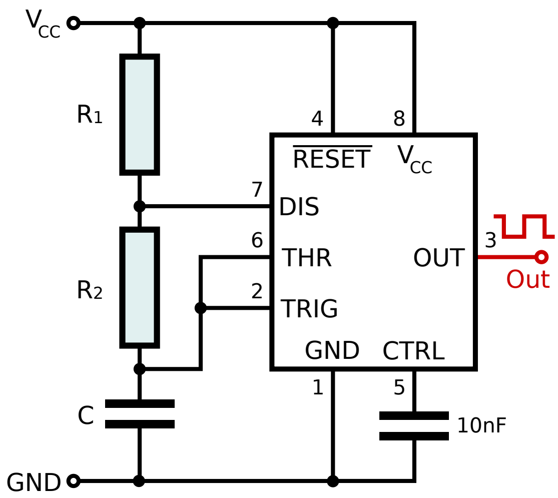
$$t = \ln(3) \cdot RC \approx 1.1RC$$

where t is in seconds, R is in ohms (resistance) and C is in farads (capacitance).

While using the timer IC in monostable mode, the main disadvantage is that the time span between any two triggering pulses must be greater than the RC time constant.[7] Conversely, ignoring closely spaced pulses is done by setting the RC time constant to be larger than



the span between spurious triggers. (Example: ignoring switch contact bouncing.)



Schematic of a 555 in astable mode

Astable In astable mode, the 555 timer puts out a continuous stream of rectangular pulses having a specified frequency. Resistor R_1 is connected between VCC and the discharge pin (pin 7) and another resistor (R_2) is connected between the discharge pin (pin 7), and the trigger (pin 2) and threshold (pin 6) pins that share a common node. Hence the capacitor is charged through R_1 and R_2, and discharged only through R_2, since pin 7 has low impedance to ground during output low intervals of the cycle, therefore discharging the capacitor.

In the astable mode, the frequency of the pulse stream depends on the values of R_1, R_2 and C:

$$f = \frac{1}{\ln(2) \cdot C \cdot (R_1 + 2R_2)}$$ [8]

The high time from each pulse is given by:

$$\text{high} = \ln(2) \cdot C \cdot (R_1 + R_2)$$

and the low time from each pulse is given by:

$$\text{low} = \ln(2) \cdot C \cdot R_2$$

where R_1 and R_2 are the values of the resistors in ohms and C is the value of the capacitor in farads.

The power capability of R_1 must be greater than $\frac{V_{cc}^2}{R_1}$.

Particularly with bipolar 555s, low values of R_1 must be avoided so that the output stays saturated near zero volts during discharge, as assumed by the above equation. Otherwise the output low time will be greater than calculated above. The first cycle will take appreciably longer than the calculated time, as the capacitor must charge from 0V to 2/3 of VCC from power-up, but only from 1/3 of VCC to 2/3 of VCC on subsequent cycles.

To have an output high time shorter than the low time (i.e., a duty cycle less than 50%) a small diode (that is fast enough for the application) can be placed in parallel with R_2, with the cathode on the capacitor side. This bypasses R_2 during the high part of the cycle so that the high interval depends only on R_1 and C, with an adjustment based the voltage drop across the diode. The voltage drop across the diode slows charging on the capacitor so that the high time is a longer than the expected and often-cited ln(2)*R_1C = 0.693 R_1C. The low time will be the same as above, 0.693 R_1C. With the bypass diode, the high time is

$$\text{high} = R_1 \cdot C \cdot \ln\left(\frac{2V_{\text{cc}} - 3V_{\text{diode}}}{V_{\text{cc}} - 3V_{\text{diode}}}\right)$$

where V_{diode} is when the diode's "on" current is 1/2 of V_{cc}/R_1 which can be determined from its datasheet or by testing. As an extreme example, when V_{cc}= 5 and V_{diode}= 0.7, high time = 1.00 R_1C which is 45% longer than the "expected" 0.693 R_1C. At the other extreme, when V_{cc}= 15 and V_{diode}= 0.3, the high time = 0.725 R_1C which is closer to the expected 0.693 R_1C. The equation reduces to the expected 0.693 R_1C if V_{diode}= 0.

The operation of RESET in this mode is not well-defined. Some manufacturers' parts will hold the output state to what it was when RESET is taken low, others will send the output either high or low.

The astable configuration, with two resistors, cannot produce a 50% duty cycle. To produce a 50% duty cycle, eliminate R1, disconnect pin 7 and connect the supply end of R2 to pin 3, the output pin. This circuit is similar to using an inverter gate as an oscillator, but with fewer components than the astable configuration, and a much higher power output than a TTL or CMOS gate. The duty cycle for either the 555 or inverter-gate timer will not be precisely 50% due to the fact the timing network is supplied from the devices output pin, which has different internal resistances depending on whether it is in the high or low state (high side drivers tend to be more resistive).

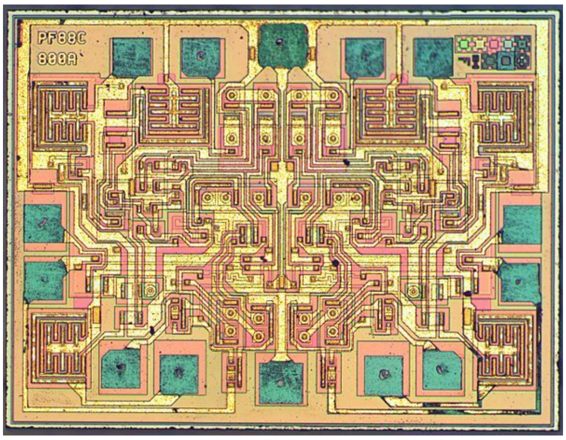
6.5.2 Specifications

These specifications apply to the NE555. Other 555 timers can have different specifications depending on the grade (military, medical, etc.).

6.5.3 Derivatives

Many pin-compatible variants, including CMOS versions, have been built by various companies. Bigger packages also exist with two or four timers on the same chip. The 555 is also known under the following type numbers:

556 dual timer



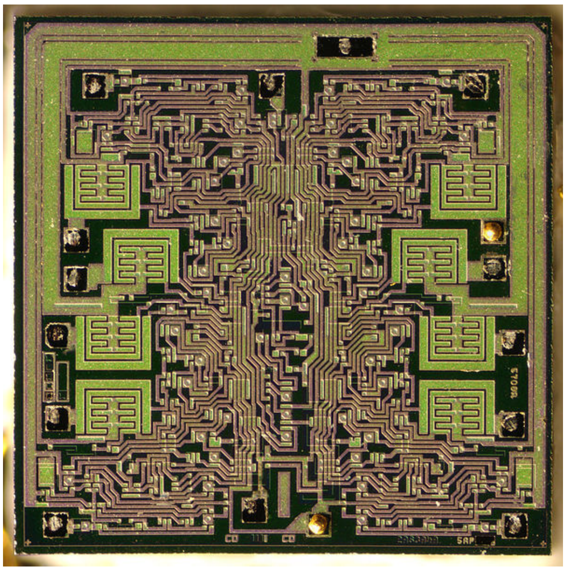
Die of a 556 dual timer manufactured by STMicroelectronics.

The dual version is called 556. It features two complete 555s in a 14 pin DIL package.

558 quad timer

The quad version is called 558 and has 16 pins. To fit four 555s into a 16 pin package the power, control voltage, and reset lines are shared by all four modules. Each module's discharge and threshold circuits are wired together internally.

6.5.4 Example applications



Die of a 558 quad timer.

Joystick interface circuit using the 558 quad timer

The Apple II microcomputer used a quad timer 558 in monostable (or "one-shot") mode to interface up to four "game paddles" or two joysticks to the host computer. It also used a single 555 for flashing the display cursor.

A similar circuit was used in the IBM PC.[10] In the joystick interface circuit of the IBM PC, the capacitor of the RC network (see Monostable Mode above) was generally a 10 nF capacitor. The resistor of the RC network consisted of the potentiometer inside the joystick along with an external resistor of 2.2 kΩ.[11] The joystick potentiometer acted as a variable resistor. By moving the joystick, the resistance of the joystick increased from a small value up to about 100 kΩ. The joystick operated at 5 V.[12]

Software running in the host computer started the process of determining the joystick position by writing to a special address (ISA bus I/O address 201h).[12][13] This would result in a trigger signal to the quad timer, which would cause the capacitor of the RC network to begin charging and cause the quad timer to output a pulse. The width of the pulse was determined by how long it took the C to charge up to 2/3 of 5 V (or about 3.33 V), which was in turn determined by the joystick position.[12][14] The software then measured the pulse width to determine the joystick position. A wide pulse represented the full-right joystick position, for example, while a narrow pulse represented the full-left joystick position.[12]

6.5.5 See also

- Counter (digital)
- Operational amplifier

- List of LM-series integrated circuits
- 4000 series, List of 4000 series integrated circuits
- 7400 series, List of 7400 series integrated circuits

6.5.6 References

[1] Ward, Jack (2004). The 555 Timer IC – An Interview with Hans Camenzind. The Semiconductor Museum. Retrieved 2010-04-05

[2] van Roon, Fig 3 & related text.

[3] Scherz, Paul (2000) "Practical Electronics for Inventors", p. 589. McGraw-Hill/TAB Electronics. ISBN 978-0-07-058078-7. Retrieved 2010-04-05.

[4] Jung, Walter G. (1983) "IC Timer Cookbook, Second Edition", pp. 40–41. Sams Technical Publishing; 2nd ed. ISBN 978-0-672-21932-0. Retrieved 2010-04-05.

[5] 555-timer-circuits.com

[6] van Roon, Chapter "Monostable Mode". (Using the 555 timer as a logic clock)

[7] national.com

[8] van Roon Chapter: "Astable operation".

[9] customsiliconsolutions.co

[10] Engdahl, pg 1.

[11] Engdahl, "Circuit diagram of PC joysyck interface"

[12] epanorama.net

[13] Eggebrecht, p. 197.

[14] Eggebrecht, pp. 197-99

6.5.7 Further reading

- *555 Timer Applications Sourcebook Experiments*; H. Berlin; BPB Publications; 218 pages; 2008; ISBN 978-8176567909.
- *Timer, Op Amp, and Optoelectronic Circuits and Projects*; Forrest Mims III; Master Publishing; 128 pages; 2004; ISBN 978-0-945053-29-3.
- *Engineer's Mini-Notebook – 555 Timer IC Circuits*; Forrest Mims III; Radio Shack; 33 pages; 1989; ASIN B000MN54A6.
- *IC Timer Cookbook*; 2nd Ed; Walter G Jung; Sams Publishing; 384 pages; 1983; ISBN 978-0-672-21932-0.
- *555 Timer Applications Sourcebook with Experiments*; Howard M Berlin; Sams Publishing; 158 pages; 1979; ISBN 978-0-672-21538-4.
- *IC 555 Projects*; E.A. Parr; Bernard Babani Publishing; 144 pages; 1978; ISBN 978-0-85934-047-2.
- *Analog Applications Manual*; Signetics; 418 pages; 1979. Chapter 6 Timers is 22 pages.

6.5.8 External links

- 555 Timer Circuits – the Astable, Monostable and Bistable
- Simple 555 timer circuits
- Java simulation of 555 oscillator circuit
- NE555 Frequency and duty cycle calculator for astable multivibrators
- Using NE555 as a Temperature DSP
- 555 Timer Tutorial by Tony van Roon
- Common Mistakes When Using a 555 Timer
- 555 and 556 Timer Circuits
- 555 using areas and examples circuits
- Working with 555 Timer Circuits Engineers Garage
- Analysis and synthesis of a 555 astable multivibrator circuit - online calculator
- Online simulations of a 555 astable multivibrator circuit - online simulator

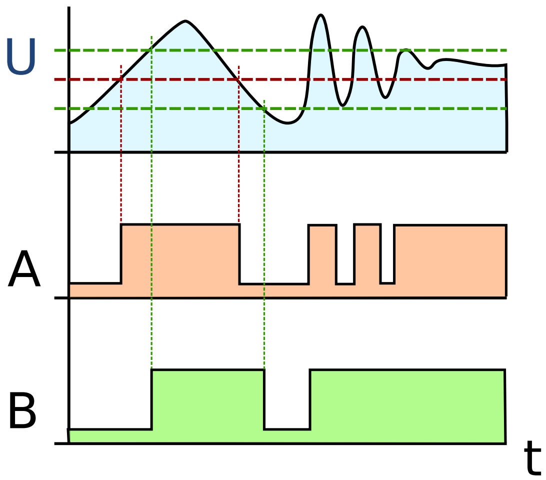
IC Datasheets

- NE555, Single Bipolar Timer, Texas Instruments
- NE556, Dual Bipolar Timer, Texas Instruments
- NE558, Quad Bipolar Timer, NXP
- LMC555, Single CMOS Timer, Texas Instruments (operates down to 1.5 Volt at 50 uAmp)
- ICM755x, Single / Dual CMOS Timer, Intersil (operates down to 2.0 Volt at 60 uAmp)
- ZSCT1555, Single CMOS Timer, Diodes Inc (operates down to 0.9 Volt at 74 uAmp)
- TS300x, Single CMOS Timers, Touchstone (operates down to 0.9 Volt at 1.0 uAmp)
- XTR65x, HiRel HiTemp Timer, X-REL (operates from −60°C to 230°C)

6.6 Schmitt trigger

In electronics a **Schmitt trigger** is a comparator circuit with hysteresis implemented by applying positive feedback to the noninverting input of a comparator or differential amplifier. It is an active circuit which converts an analog input signal to a digital output signal. The circuit is named a "trigger" because the output retains its value until the input changes sufficiently to trigger a change. In the non-inverting configuration, when the input is higher than a chosen threshold, the output is high. When the input is below a different (lower) chosen threshold the output is low, and when the input is between the two levels the output retains its value. This dual threshold action is called *hysteresis* and implies that the Schmitt trigger possesses memory and can act as a bistable multivibrator (latch or flip-flop). There is a close relation between the two kinds of circuits: a Schmitt trigger can be converted into a latch and a latch can be converted into a Schmitt trigger.

Schmitt trigger devices are typically used in signal conditioning applications to remove noise from signals used in digital circuits, particularly mechanical contact bounce. They are also used in closed loop negative feedback configurations to implement relaxation oscillators, used in function generators and switching power supplies.



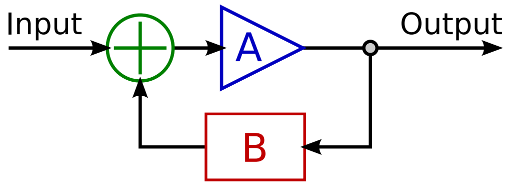
A noisy signal (U) fed into a comparator (A) and a Schmitt trigger (B). The green dotted lines are the circuit's switching thresholds. The Schmitt trigger tends to remove noise from the signal.

6.6.1 Invention

The Schmitt trigger was invented by the American scientist Otto H. Schmitt in 1934 while he was still a graduate student,[1] later described in his doctoral dissertation (1937) as a "thermionic trigger."[2] It was a direct result of Schmitt's study of the neural impulse propagation in squid nerves.[2]

6.6.2 Implementation

Fundamental idea



Block diagram of a Schmitt trigger circuit. It is a system with positive feedback in which the output signal fed back into the input causes the amplifier A *to switch rapidly from one saturated state to the other when the input crosses a threshold.*
*:***A** *> 1 is the amplifier gain :***B** *< 1 is the feedback transfer function*

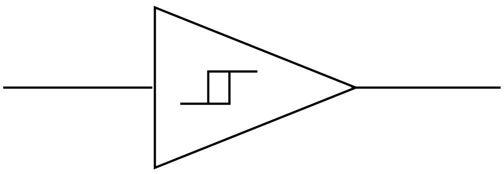
Circuits with hysteresis are based on the fundamental positive feedback idea: any active circuit can be made to behave as a Schmitt trigger by applying a positive feedback so that the loop gain is more than one. The positive feedback is introduced by adding a part of the output voltage to the input voltage. These circuits contain an 'attenuator' (the B box in the figure on the right) and a 'summer' (the circle with "+" inside) in addition to an amplifier acting as a comparator. There are three specific techniques for implementing this general idea. The first two of them are dual versions (series and parallel) of the general positive feedback system. In these configurations, the output voltage increases the effective difference input voltage of the comparator by 'decreasing the threshold' or by 'increasing the circuit input voltage'; the threshold and memory properties are incorporated in one element. In the third technique, the threshold and memory properties are separated.

Dynamic threshold (series feedback): when the input voltage crosses the threshold in some direction the very circuit changes its own threshold to the opposite direction. For this purpose, it subtracts a part of its output voltage from the threshold (it is equal to adding voltage to the input voltage). Thus the output affects the threshold and does not impact on the input voltage. These circuits are implemented by a differential amplifier with 'series positive feedback' where the input is connected to the inverting input and the output - to the non-inverting input. In this arrangement, attenuation and summation are separated: a voltage divider acts as an attenuator and the loop acts as a simple series voltage summer. Examples are the classic transistor emitter-coupled Schmitt trigger, the op-amp inverting Schmitt trigger, etc.

Modified input voltage (parallel feedback): when the input voltage crosses the threshold in some direction the circuit changes the very input voltage in the same direction (now it adds a part of its output voltage directly to the input voltage). Thus the output "helps" the input voltage and does not affect the threshold. These circuits can be implemented by a single-ended non-inverting amplifier with 'parallel positive feedback' where the input and the output sources are connected through resistors to the input. The two resistors form a weighted parallel summer incorporating both the attenuation and summation. Examples are the less familiar collector-base coupled Schmitt trigger, the op-amp non-inverting Schmitt trigger, etc.

Some circuits and elements exhibiting negative resistance can also act in a similar way: negative impedance converters (NIC), neon lamps, tunnel diodes (e.g., a diode with an “N"-shaped current–voltage characteristic in the first quadrant), etc. In the last case, an oscillating input will cause the diode to move from one rising leg of the “N” to the other and back again as the input crosses the rising and falling switching thresholds.

Two different unidirectional thresholds are assigned in this case to two separate open-loop comparators (without hysteresis) driving a bistable multivibrator (latch) or flip-flop). The trigger is toggled high when the input voltage crosses down to up the high threshold and low when the input voltage crosses up to down the low threshold. Again, there is a positive feedback but now it is concentrated only in the memory cell. Examples are the 555 timer and the switch debounce circuit.[3]

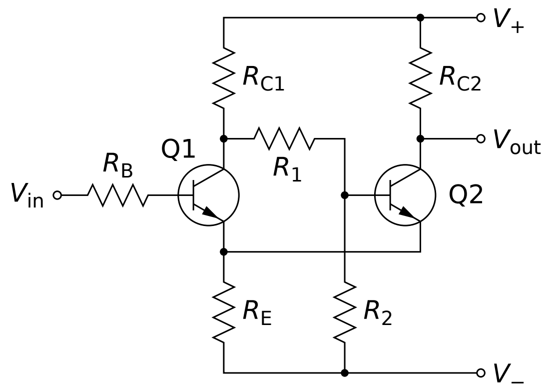


A symbol of Schmitt trigger shown with a non-inverting hysteresis curve embedded in a buffer. Schmitt triggers can also be shown with inverting hysteresis curves and may be followed by bubbles. The documentation for the particular Schmitt trigger being used must be consulted to determine whether the device is non-inverting (i.e., where positive output transitions are caused by positive-going inputs) or inverting (i.e., where positive output transitions are caused by negative-going inputs).

The symbol for Schmitt triggers in circuit diagrams is a triangle with a symbol inside representing its ideal hysteresis curve.

Transistor Schmitt triggers

Classic emitter-coupled circuit The original Schmitt trigger is based on the dynamic threshold idea that is implemented by a voltage divider with a switchable upper leg (the collector resistors RC_1 and RC_2) and a steady lower leg (RE). Q1 acts as a comparator with a differential input (Q1 base-emitter junction) consisting of an inverting (Q1 base) and a non-inverting (Q1 emitter) inputs. The input voltage is applied to the inverting input; the



Schmitt trigger implemented by two emitter-coupled transistor stages

output voltage of the voltage divider is applied to the non-inverting input thus determining its threshold. The comparator output drives the second common collector stage Q2 (an *emitter follower*) through the voltage divider R_1-R_2. The emitter-coupled transistors Q1 and Q2 actually compose an electronic double throw switch that switches over the upper legs of the voltage divider and changes the threshold in a different (to the input voltage) direction.

This configuration can be considered as a differential amplifier with series positive feedback between its non-inverting input (Q2 base) and output (Q1 collector) that forces the transition process. There is also a smaller negative feedback introduced by the emitter resistor RE. To make the positive feedback dominate over the negative one and to obtain a hysteresis, the proportion between the two collector resistors is chosen $RC_1 > RC_2$. Thus less current flows through and less voltage drop is across RE when Q1 is switched on than in the case when Q2 is switched on. As a result, the circuit has two different thresholds in regard to ground (V- in the image).

Operation **Initial state.** For the NPN transistors shown on the right, imagine the input voltage is below the shared emitter voltage (high threshold for concreteness) so that Q1 base-emitter junction is reverse-biased and Q1 does not conduct. The Q2 base voltage is determined by the mentioned divider so that Q2 is conducting and the trigger output is in the low state. The two resistors RC_2 and RE form another voltage divider that determines the high threshold. Neglecting VBE, the high threshold value is approximately

$$V_{\mathrm{HT}} = \frac{R_{\mathrm{E}}}{R_{\mathrm{E}} + R_{\mathrm{C2}}} V_+$$

The output voltage is low but well above ground. It is approximately equal to the high threshold and may not be low enough to be a logical zero for next digital circuits. This may require additional shifting circuit following the trigger circuit.

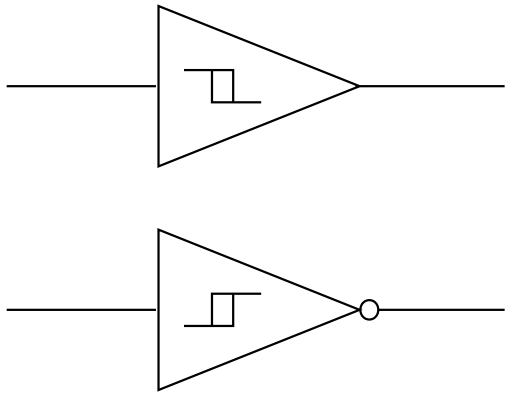
Crossing up the high threshold. When the input voltage (Q1 base voltage) rises slightly above the voltage across the emitter resistor RE (the high threshold), Q1 begins conducting. Its collector voltage goes down and Q2 begins going cut-off, because the voltage divider now provides lower Q2 base voltage. The common emitter voltage follows this change and goes down thus making Q1 conduct more. The current begins steering from the right leg of the circuit to the left one. Although Q1 is more conducting, it passes less current through RE (since $RC_1 > RC_2$); the emitter voltage continues dropping and the effective Q1 base-emitter voltage continuously increases. This avalanche-like process continues until Q1 becomes completely turned on (saturated) and Q2 turned off. The trigger is transitioned to the high state and the output (Q2 collector) voltage is close to V+. Now, the two resistors RC_1 and RE form a voltage divider that determines the low threshold. Its value is approximately

$$V_{\mathrm{LT}} = \frac{R_{\mathrm{E}}}{R_{\mathrm{E}} + R_{\mathrm{C1}}} V_{+}$$

Crossing down the low threshold. With the trigger now in the high state, if the input voltage lowers enough (below the low threshold), Q1 begins cutting-off. Its collector current reduces; as a result, the shared emitter voltage lowers slightly and Q1 collector voltage rises significantly. The R_1-R_2 voltage divider conveys this change to the Q2 base voltage and it begins conducting. The voltage across RE rises, further reducing the Q1 base-emitter potential in the same avalanche-like manner, and Q1 ceases to conduct. Q2 becomes completely turned on (saturated) and the output voltage becomes low again.

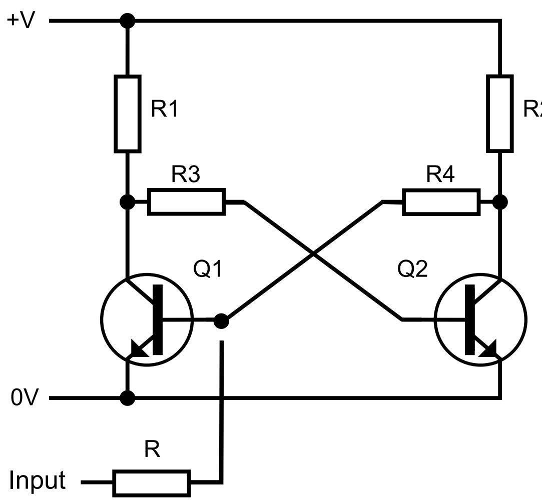
Variations **Non-inverting circuit.** The classic non-inverting Schmitt trigger can be turned into an inverting trigger by taking V_{out} from the emitters instead of from a Q2 collector. In this configuration, the output voltage is equal to the dynamic threshold (the shared emitter voltage) and both the output levels stay away from the supply rails. Another disadvantage is that the load changes the thresholds so, it has to be high enough. The base resistor RB is obligatory to prevent the impact of the input voltage through Q1 base-emitter junction on the emitter voltage.

Direct-coupled circuit. To simplify the circuit, the R_1–R_2 voltage divider can be omitted connecting Q1 collector directly to Q2 base. The base resistor RB can be omitted as well so that the input voltage source drives directly Q1's base.[4] In this case, the common emitter voltage and Q1 collector voltage are not suitable for outputs. Only Q2 collector should be used as an output since, when the input voltage exceeds the high threshold and Q1 saturates, its base-emitter junction is forward biased and transfers the input voltage variations directly to the emitters. As a result, the common emitter voltage and Q1 collector voltage follow the input voltage. This situation is typical for over-driven transistor differential amplifiers and ECL



Symbol depicting an inverting Schmitt trigger by showing an inverted hysteresis curve inside a buffer. Other symbols show a hysteresis curve (which may be inverting or non-inverting) embedded in a buffer followed by a bubble, which is similar to the traditional symbol for a digital inverter that shows a buffer followed by a bubble. In general, the direction of the Schmitt trigger (inverting or non-inverting) is not necessarily clear from the symbol because multiple conventions are used, even with the same manufacturer. There are several factors leading to such ambiguity,[nb 1] These circumstances may warrant a closer investigation of the documentation for each particular Schmitt trigger.

gates.



BJT bistable collector-base coupled circuit can be converted to a Schmitt trigger by connecting an additional base resistor to one of the bases

Collector-base coupled circuit Like every latch, the fundamental collector-base coupled bistable circuit possesses a hysteresis. So, it can be converted to a Schmitt trigger by connecting an additional base resistor R to one of the inputs (Q1 base in the figure). The two resistors R and R_4 form a parallel voltage summer (the circle in the ballock diagram above) that sums output (Q2 collector) voltage and the input voltage, and drives the single-ended transistor “comparator” Q1. When the base voltage crosses the threshold ($VBE_0 \infty 0.65$ V) in some direction, a part of Q2’s collector voltage is added in the same direction to the input voltage. Thus the output modifies the input voltage by means of parallel positive feedback and does not affect the threshold (the base-emitter voltage).

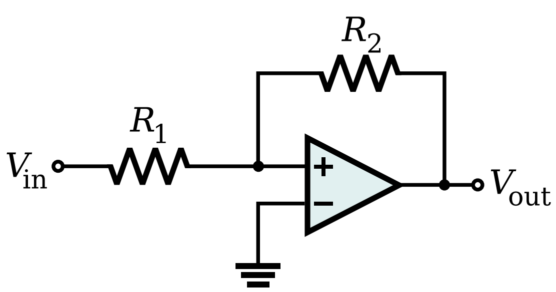
Comparison between emitter- and collector-coupled circuit

The emitter-coupled version has the advantage that the input transistor is backward-biased when the input voltage is quite below the high threshold so the transistor is surely cut-off. It was important when germanium transistors were used for implementing the circuit and this advantage has determined its popularity. The input base resistor can be omitted since the emitter resistor limits the current when the input base-emitter junction is forward-biased.

The emitter-coupled Schmitt trigger has not low enough level at output *logical zero* and needs an additional output shifting circuit. The collector-coupled Schmitt trigger has extremely low (almost zero) output level at output *logical zero*.

Op-amp implementations

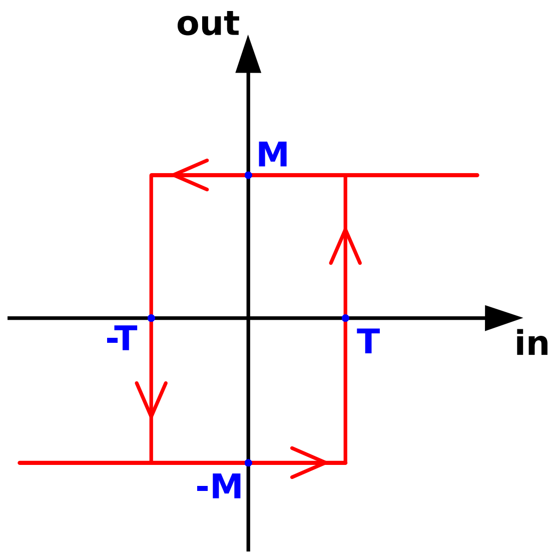
Schmitt triggers are commonly implemented using an operational amplifier or the more dedicated comparator.[nb 2] An open-loop op-amp and comparator may be considered as an analog-digital device having analog inputs and a digital output that extracts the sign of the voltage difference between its two inputs.[nb 3] The positive feedback is applied by adding a part of the output voltage to the input voltage in series or parallel manner. Due to the extremely high op-amp gain, the loop gain is also high enough and provides the avalanche-like process.



Schmitt trigger implemented by a non-inverting comparator

Non-inverting Schmitt trigger In this circuit, the two resistors R_1 and R_2 form a parallel voltage summer. It adds a part of the output voltage to the input voltage thus “helping” it during and after switching that occurs when the resulting voltage is near ground. This *parallel positive feedback* creates the needed hysteresis that is controlled by the proportion between the resistances of R_1 and R_2. The output of the parallel voltage summer is single-ended (it produces voltage with respect to ground) so the circuit does not need an amplifier with a differential input. Since conventional op-amps have a differential input, the inverting input is grounded to make the reference point zero volts.

The output voltage always has the same sign as the *op-amp input voltage* but it does not always have the same sign as the *circuit input voltage* (the signs of the two input voltages can differ). When the circuit input voltage is above the high threshold or below the low threshold, the output voltage has the same sign as the *circuit input voltage* (the circuit is non-inverting). It acts like a comparator that switches at a different point depending on whether the output of the comparator is high or low. When the circuit input voltage is between the thresholds, the output voltage is undefined and it depends on the last state (the circuit behaves as an elementary latch).

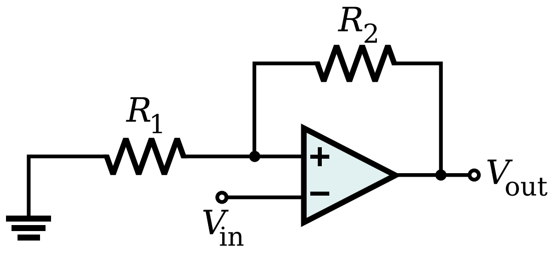


Typical hysteresis curve (non-inverting) which matches the curve shown on a Schmitt trigger symbol

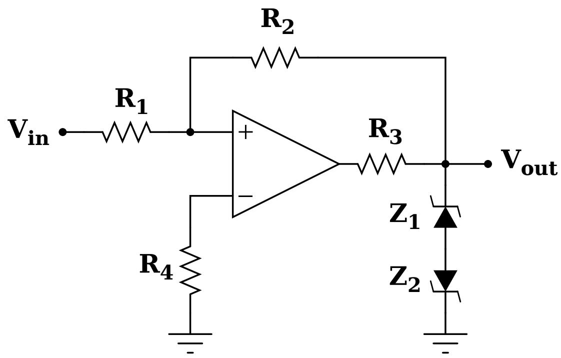
For instance, if the Schmitt trigger is currently in the high state, the output will be at the positive power supply rail (+VS). The output voltage V_+ of the resistive summer can be found by applying the superposition theorem:

$$V_+ = \frac{R_2}{R_1 + R_2} \cdot V_{\text{in}} + \frac{R_1}{R_1 + R_2} \cdot V_{\text{s}}$$

The comparator will switch when V_+=0. Then $R_2 \cdot V_{\text{in}} = -R_1 \cdot V_{\text{s}}$ (the same result can be obtained by applying the current conservation principle). So V_{in} must drop below $-\frac{R_1}{R_2} V_s$ to get the output to switch. Once the comparator output has switched to $-VS$, the threshold becomes $+\frac{R_1}{R_2} V_s$ to switch back to high. So this circuit creates a switching band centered on zero, with trigger levels $\pm\frac{R_1}{R_2}V_s$ (it can be shifted to the left or the right by applying a bias voltage to the inverting input). The input voltage must rise above the top of the band, and then below the bottom of the band, for the output to switch on (plus) and then back off (minus). If R_1 is zero or R_2 is infinity (i.e., an open circuit), the band collapses to zero width, and it behaves as a standard comparator. The transfer characteristic is shown in the picture on the left. The value of the threshold T is given by $\frac{R_1}{R_2}V_s$ and the maximum value of the output M is the power supply rail.



Schmitt trigger implemented by an inverting comparator



A practical Schmitt trigger configuration with precise thresholds

A unique property of circuits with parallel positive feedback is the impact on the input source. In circuits with negative parallel feedback (e.g., an inverting amplifier), the virtual ground at the inverting input separates the input source from the op-amp output. Here there is no virtual ground, and the steady op-amp output voltage is applied through R_1-R_2 network to the input source. The op-amp output passes an opposite current through the input source (it injects current into the source when the input voltage is positive and it draws current from the source when it is negative).

A practical Schmitt trigger with precise thresholds is shown in the figure on the right. The transfer characteristic has exactly the same shape of the previous basic configuration, and the threshold values are the same as well. On the other hand, in the previous case, the output voltage was depending on the power supply, while now it is defined by the Zener diodes (which could also be replaced with a single double-anode Zener diode). In this configuration, the output levels can be modified by appropriate choice of Zener diode, and these levels are resistant to power supply fluctuations (i.e., they increase the PSRR of the comparator). The resistor R_3 is there to limit the current through the diodes, and the resistor R_4 minimizes the input voltage offset caused by the comparator's input leakage currents (see *limitations of real op-amps*).

Inverting Schmitt trigger In the inverting version, the attenuation and summation are separated. The two resistors R_1 and R_2 act only as a "pure" attenuator (voltage divider). The input loop acts as a simple series voltage summer that adds a part of the output voltage in series to the circuit input voltage. This *series positive feedback* creates the needed hysteresis that is controlled by the proportion between the resistances of R_1 and the whole resistance (R_1 and R_2). The effective voltage applied to the op-amp input is floating so the op-amp must have a differential input.

The circuit is named *inverting* since the output voltage always has an opposite sign to the input voltage when it is out of the hysteresis cycle (when the input voltage is above the high threshold or below the low threshold). However, if the input voltage is within the hysteresis cycle (between the high and low thresholds), the circuit can be inverting as well as non-inverting. The output voltage is undefined and it depends on the last state so the circuit behaves like an elementary latch.

To compare the two versions, the circuit operation will be considered at the same conditions as above. If the Schmitt trigger is currently in the high state, the output will be at the positive power supply rail (+VS). The output voltage V_+ of the voltage divider is:

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

The comparator will switch when $V_{in} = V_+$. So V_{in} must exceed above this voltage to get the output to switch. Once the comparator output has switched to $-VS$, the threshold becomes $-\frac{R_1}{R_1+R_2}V_s$ to switch back to high. So this circuit creates a switching band centered on zero, with trigger levels $\pm\frac{R_1}{R_1+R_2}V_s$ (it can be shifted to the left or the right by connecting R_1 to a bias voltage). The input voltage must rise above the top of the band, and then below the bottom of the band, for the output to switch off (minus) and then back on (plus). If R_1 is zero (i.e., a short circuit) or R_2 is infinity, the band collapses to zero width, and it behaves as a standard comparator.

In contrast with the parallel version, this circuit does not impact on the input source since the source is separated from the voltage divider output by the high op-amp input differential impedance.

6.6.3 Applications

Schmitt triggers are typically used in open loop configurations for noise immunity and closed loop configurations to implement function generators.

Noise immunity

One application of a Schmitt trigger is to increase the noise immunity in a circuit with only a single input threshold. With only one input threshold, a noisy input signal [nb 4] near that threshold could cause the output to switch rapidly back and forth from noise alone. A noisy Schmitt Trigger input signal near one threshold can cause only one switch in output value, after which it would have to move beyond the other threshold in order to cause another switch.

For example, an amplified infrared photodiode may generate an electric signal that switches frequently between its absolute lowest value and its absolute highest value. This signal is then low-pass filtered to form a smooth signal that rises and falls corresponding to the relative amount of time the switching signal is on and off. That filtered output passes to the input of a Schmitt trigger. The net effect is that the output of the Schmitt trigger only passes from low to high after a received infrared signal excites the photodiode for longer than some known delay, and once the Schmitt trigger is high, it only moves low after the infrared signal ceases to excite the photodiode for longer than a similar known delay. Whereas the photodiode is prone to spurious switching due to noise from the environment, the delay added by the filter and Schmitt trigger ensures that the output only switches when there is certainly an input stimulating the device.

Schmitt triggers are common in many switching circuits for similar reasons (e.g., for switch debouncing).

List of IC including input Schmitt triggers

The following 7400 series devices include a Schmitt trigger on their input or on each of their inputs:

- 7413: Dual Schmitt trigger 4-input NAND Gate
- 7414: Hex Schmitt trigger Inverter
- 7418: Dual Schmitt trigger 4-input NAND Gate
- 7419: Hex Schmitt trigger Inverter
- 74121: Monostable Multivibrator with Schmitt Trigger Inputs
- 74132: Quad 2-input NAND Schmitt Trigger
- 74221: Dual Monostable Multivibrator with Schmitt Trigger Input
- 74232: Quad NOR Schmitt Trigger
- 74310: Octal Buffer with Schmitt Trigger Inputs
- 74340: Octal Buffer with Schmitt Trigger Inputs and three-state inverted outputs
- 74341: Octal Buffer with Schmitt Trigger Inputs and three-state noninverted outputs
- 74344: Octal Buffer with Schmitt Trigger Inputs and three-state noninverted outputs
- 74(HC/HCT)**7**541 Octal Buffer with Schmitt Trigger Inputs and Three-State Noninverted Outputs
- SN74LV8151 is a 10-bit universal Schmitt-trigger buffer with 3-state outputs

A number of 4000 series devices include a Schmitt trigger on inputs, for example:

- 4017: Decade Counter with Decoded Outputs
- 4020: 14-Stage Binary Ripple Counter
- 4022: Octal Counter with Decoded Outputs
- 4024: 7-Stage Binary Ripple Counter
- 4040: 12-Stage Binary Ripple Counter
- 4093: Quad 2-Input NAND
- 40106: Hex Inverter
- 14538: Dual Monostable Multivibrator

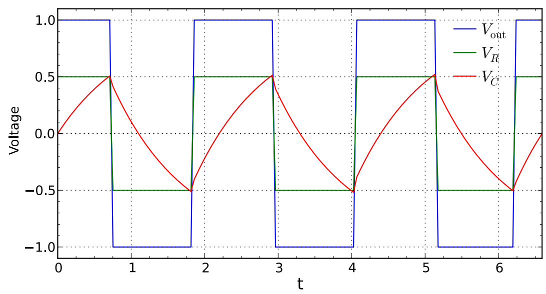
Dual Schmitt input configurable single-gate CMOS logic, AND, OR, XOR, NAND, NOR, XNOR

- NC7SZ57 Fairchild
- NC7SZ58 Fairchild
- SN74LVC1G57 Texas Instruments
- SN74LVC1G58 Texas Instruments

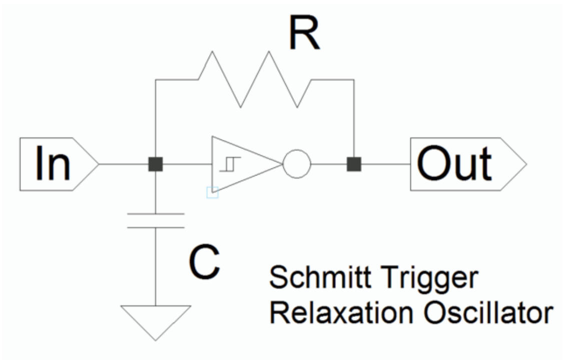
Use as an oscillator

Main article: Relaxation oscillator

A Schmitt trigger is a bistable multivibrator, and it can be used to implement another type of multivibrator, the relaxation oscillator. This is achieved by connecting a single RC integrating circuit between the output and the input of an inverting Schmitt trigger. The output will be a continuous square wave whose frequency depends on the values of R and C, and the threshold points of the Schmitt trigger. Since multiple Schmitt trigger circuits can be provided by a single integrated circuit (e.g. the 4000 series CMOS device type 40106 contains 6 of them), a spare section of the IC can be quickly pressed into service as a



Output and capacitor waveforms for comparator-based relaxation oscillator



A Schmitt Trigger-based implementation of a relaxation oscillator

simple and reliable oscillator with only two external components.

Here, a comparator-based Schmitt trigger is used in its inverting configuration. Additionally, slow negative feedback is added with an integrating RC network. The result, which is shown on the right, is that the output automatically oscillates from VSS to VDD as the capacitor charges from one Schmitt trigger threshold to the other.

6.6.4 See also

- Hysteresis
- Positive feedback
- Operational amplifier applications
- Bistable multivibrator circuit
- Threshold detector with hysteresis
- Comparator

6.6.5 Notes

[1] One factor contributing to ambiguity is that one simple transistor-based realization of a Schmitt trigger is naturally inverting, with a non-inverting Schmitt trigger sometimes consisting of such an inverting implementation followed by an inverter. An additional inverter may be added for buffering a stand-alone inverting configuration. Consequently, inverting configurations within an integrated circuit may be naturally inverting, while non-inverting configurations are implemented with a single inverter, and stand-alone inverting configurations may be implemented with two inverters. As a result, symbols that combine inverting bubbles and hysteresis curves may be using the hysteresis curve to describe the entire device or the embedded Schmitt trigger only.

[2] Usually, negative feedback is used in op-amp circuits. Some operational amplifiers are designed to be used only in negative-feedback configurations that enforce a negligible difference between the inverting and non-inverting inputs. They incorporate input-protection circuitry that prevent the inverting and non-inverting inputs from operating far away from each other. For example, clipper circuits made up of two general purpose diodes with opposite bias in parallel or two Zener diodes with opposite bias in series (i.e., a double-anode Zener diode) are sometimes used internally across the two inputs of the operational amplifier. In these cases, the operational amplifiers will fail to function well as comparators. Conversely, comparators are designed under the assumption that the input voltages can differ significantly.

[3] When the non-inverting (+) input is at a higher voltage than the inverting (−) input, the comparator output switches nearly to $+VS$, which is its high supply voltage. When the non-inverting (+) input is at a lower voltage than the inverting (−) input, the comparator output switches nearly to -VS, which is its low supply voltage.

[4] Where the noise amplitude is assumed to be small compared to the change in Schmitt trigger threshold.

6.6.6 References

[1] Otto H. Schmitt, A Thermionic Trigger, Journal of Scientific Instruments 15 (January 1938): 24–26.

[2] August 2004 issue of the Pavek Museum of Broadcasting Newsletter - http://160.94.102.47/Otto_Images/PavekOHSbio.pdf

[3] Debouncing switches with an SR latch

[4] 7414 datasheet

6.6.7 External links

6.7 Shift register

In digital circuits, a **shift register** is a cascade of flip flops, sharing the same clock, in which the output of each flip-flop is connected to the 'data' input of the next flip-flop in the chain, resulting in a circuit that shifts by one position the 'bit array' stored in it, 'shifting in' the data present at its input and 'shifting out' the last bit in the array, at each transition of the clock input.

More generally, a shift register may be multidimensional, such that its 'data in' and stage outputs are themselves bit arrays: this is implemented simply by running several shift registers of the same bit-length in parallel.

Shift registers can have both parallel and serial inputs and outputs. These are often configured as 'serial-in, parallel-out' (SIPO) or as 'parallel-in, serial-out' (PISO). There are also types that have both serial and parallel input and types with serial and parallel output. There are also 'bidirectional' shift registers which allow shifting in both directions: L→R or R→L. The serial input and last output of a shift register can also be connected to create a 'circular shift register'.

6.7.1 Serial-in and Serial-out (SISO)

Destructive readout

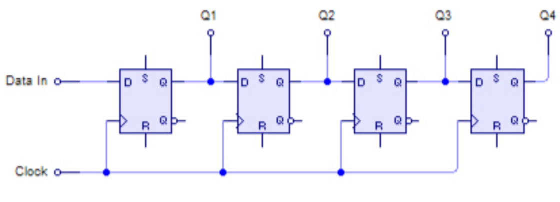
These are the simplest kind of shift registers. The data string is presented at 'Data In', and is shifted right one stage each time 'Data Advance' is brought high. At each advance, the bit on the far left (i.e. 'Data In') is shifted into the first flip-flop's output. The bit on the far right (i.e. 'Data Out') is shifted out and lost.

The data are stored after each flip-flop on the 'Q' output, so there are four storage 'slots' available in this arrangement, hence it is a 4-bit Register. To give an idea of the shifting pattern, imagine that the register holds 0000 (so all storage slots are empty). As 'Data In' presents 1,0,1,1,0,0,0,0 (in that order, with a pulse at 'Data Advance' each time—this is called clocking or strobing) to the register, this is the result. The left hand column corresponds to the left-most flip-flop's output pin, and so on.

So the serial output of the entire register is 10110000. It can be seen that if data were to be continued to input, it would get exactly what was put in, but offset by four 'Data Advance' cycles. This arrangement is the hardware equivalent of a queue. Also, at any time, the whole register can be set to zero by bringing the reset (R) pins high.

This arrangement performs *destructive readout* - each datum is lost once it has been shifted out of the right-most bit.

6.7.2 Serial-in, parallel-out (SIPO)



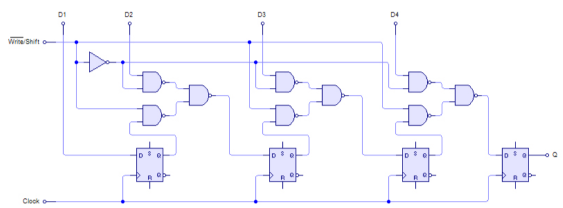
This configuration allows conversion from serial to parallel format. Data is input serially, as described in the SISO section above. Once the data has been clocked in, it may be either read off at each output simultaneously, or it can be shifted out

In this configuration, each flip-flop is edge triggered. The initial flip-flop operates at the given clock frequency. Each subsequent flip-flop halves the frequency of its predecessor, which doubles its duty cycle. As a result, it takes twice as long for the rising/falling edge to trigger each subsequent flip-flop; this staggers the serial input in the time domain, leading to parallel output.

In cases where the parallel outputs should not change during the serial loading process, it is desirable to use a latched or buffered output. In a latched shift register (such as the 74595) the serial data is first loaded into an internal buffer register, then upon receipt of a load signal the state of the buffer register is copied into a set of output registers. In general, the practical application of the serial-in/parallel-out shift register is to convert data from serial format on a single wire to parallel format on multiple wires.

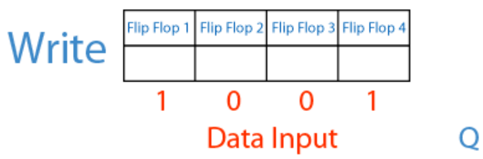
6.7.3 Parallel-in, Serial-out (PISO)

This configuration has the data input on lines D1 through D4 in parallel format, being D1 the MSB. To write the data to the register, the Write/Shift control line must be held LOW. To shift the data, the W/S control line is brought HIGH and the registers are clocked. The arrangement now acts as a SISO shift register, with D1 as the Data Input. However, as long as the number of clock cycles is not more than the length of the data-string, the Data Output, Q, will be the parallel data read off in order.



4-Bit PISO Shift Register

The animation below shows the write/shift sequence, including the internal state of the shift register.



6.7.4 Uses

One of the most common uses of a shift register is to convert between serial and parallel interfaces. This is useful as many circuits work on groups of bits in parallel, but serial interfaces are simpler to construct. Shift registers can be used as simple delay circuits. Several bidirectional shift registers could also be connected in parallel for a hardware implementation of a stack.

SIPO registers are commonly attached to the output of microprocessors when more General Purpose Input/Output pins are required than are available. This allows several binary devices to be controlled using only two or three pins, but slower than parallel I/O - the devices in question are attached to the parallel outputs of the shift register, then the desired state of all those devices can be sent out of the microprocessor using a single serial connection. Similarly, PISO configurations are commonly used to add more binary inputs to a microprocessor than are available - each binary input (i.e. a button or more complicated circuitry) is attached to a parallel input of the shift register, then the data is sent back via serial to the microprocessor using several fewer lines than originally required.

Shift registers can also be used as pulse extenders. Compared to monostable multivibrators, the timing has no dependency on component values, however it requires external clock and the timing accuracy is limited by a granularity of this clock. Example: Ronja Twister, where five 74164 shift registers create the core of the timing logic this way (schematic).

In early computers, shift registers were used to handle data processing: two numbers to be added were stored in two shift registers and clocked out into an arithmetic and logic unit (ALU) with the result being fed back to the input of one of the shift registers (the accumulator) which was one bit longer since binary addition can only result in an answer that is the same size or one bit longer.

Many computer languages include instructions to 'shift right' and 'shift left' the data in a register, effectively dividing by two or multiplying by two for each place shifted.

Very large serial-in serial-out shift registers (thousands of bits in size) were used in a similar manner to the earlier delay line memory in some devices built in the early 1970s. Such memories were sometimes called *circulating memory*. For example, the Datapoint 3300 terminal stored its display of 25 rows of 72 columns of upper-case characters using fifty-four 200-bit shift registers, arranged in six tracks of nine packs each, providing storage for 1800 six-bit characters. The shift register design meant that scrolling the terminal display could be accomplished by simply pausing the display output to skip one line of characters.[1]

6.7.5 History

One of the first known examples of a shift register was in the Mark 2 Colossus, a code-breaking machine built in 1944. It was a six-stage device built of vacuum tubes and thyratrons.[2] A shift register was also used in the IAS machine, built by John von Neumann and others at the Institute for Advanced Study in the late 1940s.

6.7.6 See also

- Delay line memory
- Linear feedback shift register (LFSR)
- Ring counter
- Serial Peripheral Interface Bus
- Shift register lookup table (SRL)

6.7.7 References

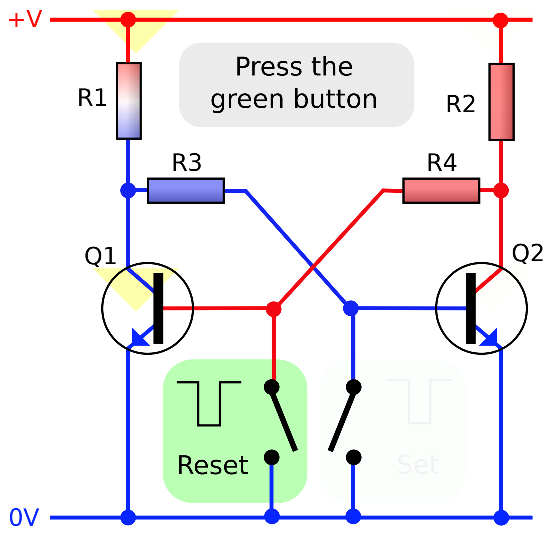
[1] bitsavers.org, *DataPoint 3300 Maintenance Manual*, December 1976.

[2] Flowers, Thomas H. (1983), "The Design of Colossus", *Annals of the History of Computing* **5** (3): 246, doi:10.1109/MAHC.1983.10079

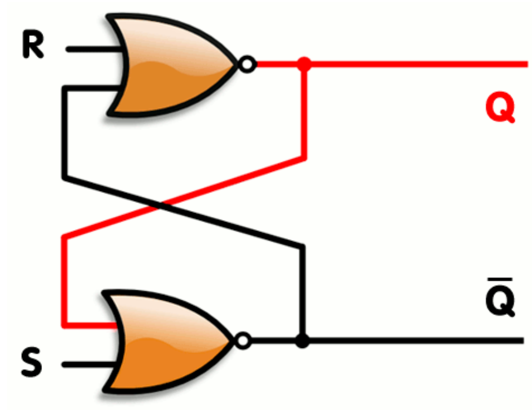
6.7.8 External links

- Shift Registers at AllAboutCircuits.com

6.8 Flip-flop



An animated interactive SR latch (R1, R2 = *1 kΩ* R3, R4 = *10 kΩ).*



An SR latch, constructed from a pair of cross-coupled NOR gates.

In electronics, a **flip-flop** or **latch** is a circuit that has two stable states and can be used to store state information. A flip-flop is a bistable multivibrator. The circuit can be made to change state by signals applied to one or more control inputs and will have one or two outputs. It is the basic storage element in sequential logic. Flip-flops and latches are a fundamental building block of digital electronics systems used in computers, communications, and many other types of systems.

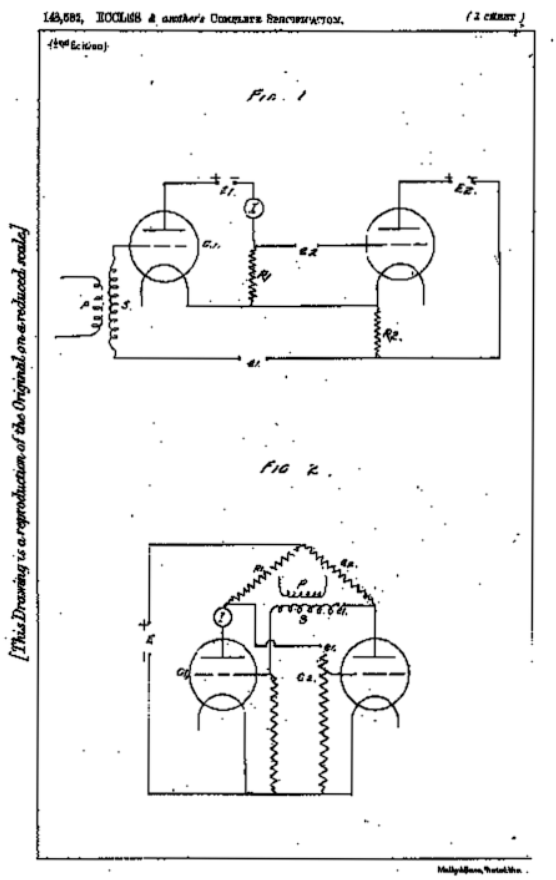
Flip-flops and latches are used as data storage elements. A flip-flop stores a single *bit* (binary digit) of data; one of its two states represents a "one" and the other represents a "zero". Such data storage can be used for storage of *state*, and such a circuit is described as sequential logic. When used in a finite-state machine, the output and next state depend not only on its current input, but also on its current state (and hence, previous inputs). It can also be used for counting of pulses, and for synchronizing variably-timed input signals to some reference timing signal.

Flip-flops can be either simple (transparent or opaque) or clocked (synchronous or edge-triggered). Although the term flip-flop has historically referred generically to both simple and clocked circuits, in modern usage it is common to reserve the term *flip-flop* exclusively for discussing clocked circuits; the simple ones are commonly called *latches*.[1][2]

Using this terminology, a latch is level-sensitive, whereas a flip-flop is edge-sensitive. That is, when a latch is enabled it becomes transparent, while a flip flop's output only changes on a single type (positive going or negative going) of clock edge.

6.8.1 History

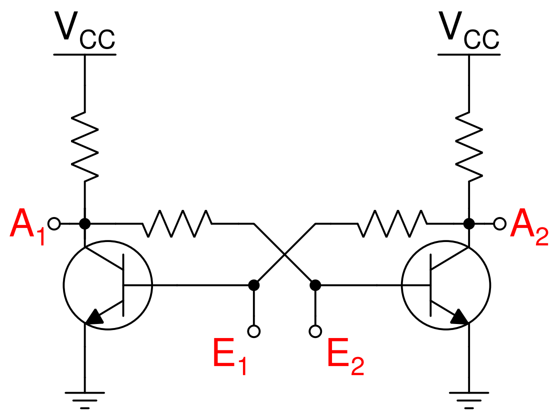
The first electronic flip-flop was invented in 1918 by the British physicists William Eccles and F. W. Jordan.[3][4] It was initially called the *Eccles–Jordan trigger circuit* and consisted of two active elements (vacuum tubes).[5] The design was used in the 1943 British Colossus codebreaking computer[6] and such circuits and their transistorized versions were common in computers even after the introduction of integrated circuits, though flip-flops made from logic gates are also common now.[7][8] Early flip-flops were known variously as trigger circuits or multivibrators.



Flip-flop schematics from the Eccles and Jordan patent filed 1918, one drawn as a cascade of amplifiers with a positive feedback path, and the other as a symmetric cross-coupled pair

According to P. L. Lindley, an engineer at the US Jet Propulsion Laboratory, the flip-flop types detailed below (RS, D, T, JK) were first discussed in a 1954 UCLA course on computer design by Montgomery Phister, and then appeared in his book *Logical Design of Digital Computers*.[9][10] Lindley was at the time working at Hughes Aircraft under Eldred Nelson, who had coined the term JK for a flip-flop which changed states when both inputs were on (a logical "one"). The other names were coined by Phister. They differ slightly from some of the definitions given below. Lindley explains that he heard the story of the JK flip-flop from Eldred Nelson, who is responsible for coining the term while working at Hughes Aircraft. Flip-flops in use at Hughes at the time were all of the type that came to be known as J-K. In designing a logical system, Nelson assigned letters to flip-flop inputs as follows: #1: A & B, #2: C & D, #3: E & F, #4: G & H, #5: J & K. Nelson used the notations "*j*-input" and "*k*-input" in a patent application filed in 1953.[11]

6.8.2 Implementation



A traditional flip-flop circuit based on bipolar junction transistors

Flip-flops can be either simple (transparent or asynchronous) or clocked (synchronous); the transparent ones are commonly called latches.[1] The word *latch* is mainly used for storage elements, while clocked devices are described as *flip-flops*.[2]

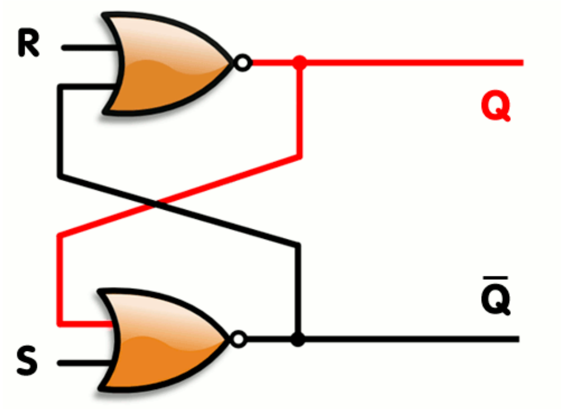
Simple flip-flops can be built around a pair of cross-coupled inverting elements: vacuum tubes, bipolar transistors, field effect transistors, inverters, and inverting logic gates have all been used in practical circuits. Clocked devices are specially designed for synchronous systems; such devices ignore their inputs except at the transition of a dedicated clock signal (known as clocking, pulsing, or strobing). Clocking causes the flip-flop to either change or retain its output signal based upon the values of the input signals at the transition. Some flip-flops change output on the rising edge of the clock, others on the falling edge.

Since the elementary amplifying stages are inverting, two stages can be connected in succession (as a cascade) to form the needed non-inverting amplifier. In this configuration, each amplifier may be considered as an active inverting feedback network for the other inverting amplifier. Thus the two stages are connected in a non-inverting loop although the circuit diagram is usually drawn as a symmetric cross-coupled pair (both the drawings are initially introduced in the Eccles–Jordan patent).

6.8.3 Flip-flop types

Flip-flops can be divided into common types: the **SR** ("set-reset"), **D** ("data" or "delay"[12]), **T** ("toggle"), and **JK** types are the common ones. The behavior of a particular type can be described by what is termed the characteristic equation, which derives the "next" (i.e., after the next clock pulse) output, Q_{next} in terms of the input signal(s) and/or the current output, Q .

Simple set-reset latches



A SR latch, constructed from a pair of cross-coupled NOR gates (an animated picture). Red and black mean logical '1' and '0', respectively.

SR NOR latch When using static gates as building blocks, the most fundamental latch is the simple *SR latch*, where S and R stand for *set* and *reset*. It can be constructed from a pair of cross-coupled NOR logic gates. The stored bit is present on the output marked Q.

While the R and S inputs are both low, feedback maintains the Q and Q outputs in a constant state, with Q the complement of Q. If S (*Set*) is pulsed high while R (*Reset*) is held low, then the Q output is forced high, and stays high when S returns to low; similarly, if R is pulsed high while S is held low, then the Q output is forced low, and stays low when R returns to low.

Note: X means don't care*, that is, either 0 or 1 is a valid value.*

The R = S = 1 combination is called a **restricted combination** or a **forbidden state** because, as both NOR gates then output zeros, it breaks the logical equation Q = **not** Q. The combination is also inappropriate in circuits where *both* inputs may go low *simultaneously* (i.e. a transition from *restricted* to *keep*). The output would lock at either 1 or 0 depending on the propagation time relations between the gates (a race condition).

To overcome the restricted combination, one can add gates to the inputs that would convert (S,R) = (1,1) to one of the non-restricted combinations. That can be:

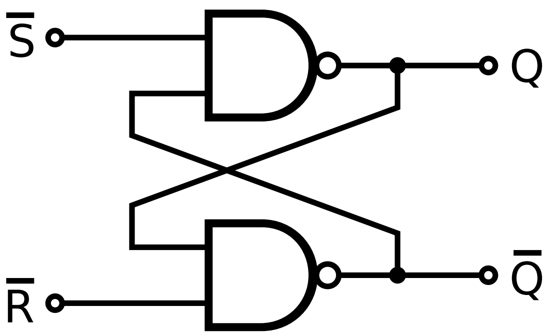
- Q = 1 (1,0) – referred to as an *S (dominated)-latch*
- Q = 0 (0,1) – referred to as an *R (dominated)-latch*

This is done in nearly every programmable logic controller.

- Keep state (0,0) – referred to as an *E-latch*

Alternatively, the restricted combination can be made to *toggle* the output. The result is the JK latch.

Characteristic: Q+ = R'Q + R'S or Q+ = R'Q + S.[14]



An SR latch

SR NAND latch This is an alternate model of the simple SR latch which is built with NAND logic gates. *Set* and *reset* now become active low signals, denoted S and R respectively. Otherwise, operation is identical to that of the SR latch. Historically, SR-latches have been predominant despite the notational inconvenience of active-low inputs.

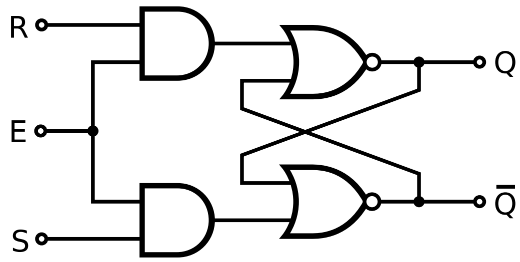
JK latch The JK latch is much less frequently used than the JK flip-flop. The JK latch follows the following state table:

Hence, the JK latch is an SR latch that is made to *toggle* its output (oscillate between 0 and 1) when passed the input combination of 11.[15] Unlike the JK flip-flop, the 11 input combination for the JK latch is not very useful because there is no clock that directs toggling.[16]

Gated latches and conditional transparency

Latches are designed to be *transparent.* That is, input signal changes cause immediate changes in output; when several *transparent* latches follow each other, using the same enable signal, signals can propagate through all of them at once. Alternatively, additional logic can be added to a simple transparent latch to make it *non-transparent* or *opaque* when another input (an "enable" input) is not asserted. By following a *transparent-high* latch with a *transparent-low* (or *opaque-high*) latch, a master–slave flip-flop is implemented.

Gated SR latch A *synchronous SR latch* (sometimes *clocked SR flip-flop*) can be made by adding a second level of NAND gates to the inverted SR latch (or a second level of AND gates to the direct SR latch). The extra NAND gates further invert the inputs so the simple SR latch becomes a gated SR latch (and a simple SR latch would transform into a gated SR latch with inverted enable).

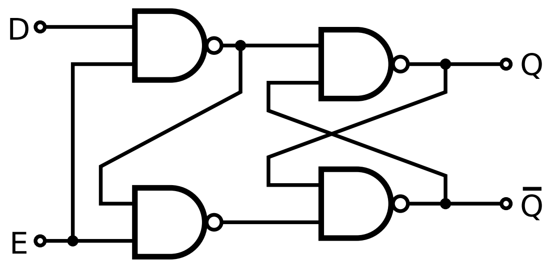


A gated SR latch circuit diagram constructed from NOR gates.

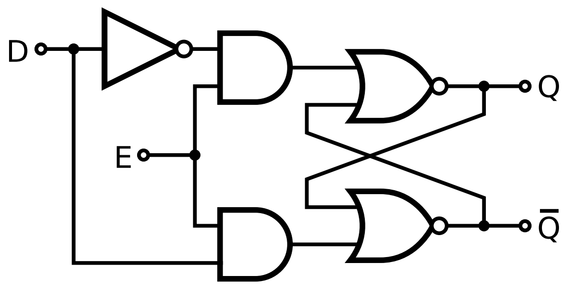
With E high (*enable* true), the signals can pass through the input gates to the encapsulated latch; all signal combinations except for (0,0) = *hold* then immediately reproduce on the (Q,Q) output, i.e. the latch is *transparent.*

With E low (*enable* false) the latch is *closed (opaque)* and remains in the state it was left the last time E was high.

The *enable* input is sometimes a clock signal, but more often a read or write strobe.

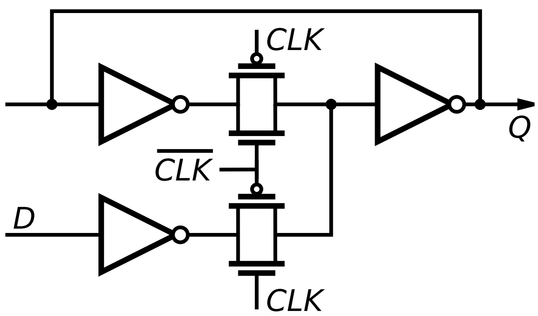


A gated D latch based on an SR NAND latch



A gated D latch based on an SR NOR latch

Gated D latch This latch exploits the fact that, in the two active input combinations (01 and 10) of a gated SR latch, R is the complement of S. The input NAND stage converts the two D input states (0 and 1) to these two input combinations for the next SR latch by inverting the data input signal. The low state of the *enable* signal produces the inactive "11" combination. Thus a gated D-latch may be considered as a *one-input synchronous SR latch*. This configuration prevents application of the restricted input combination. It is also known as *transparent latch*, *data latch*, or simply *gated latch*. It has a *data* input and an *enable* signal (sometimes named *clock*, or *control*). The word *transparent* comes from the fact that, when the en-



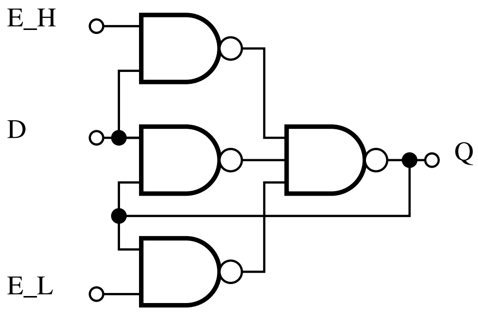
A gated D latch in pass transistor logic, similar to the ones in the CD4042 or the CD74HC75 integrated circuits.

able input is on, the signal propagates directly through the circuit, from the input D to the output Q.

Transparent latches are typically used as I/O ports or in asynchronous systems, or in synchronous two-phase systems (synchronous systems that use a two-phase clock), where two latches operating on different clock phases prevent data transparency as in a master–slave flip-flop.

Latches are available as integrated circuits, usually with multiple latches per chip. For example, 74HC75 is a quadruple transparent latch in the 7400 series.

The truth table shows that when the *e*nable/*c*lock input is 0, the D input has no effect on the output. When E/C is high, the output equals D.



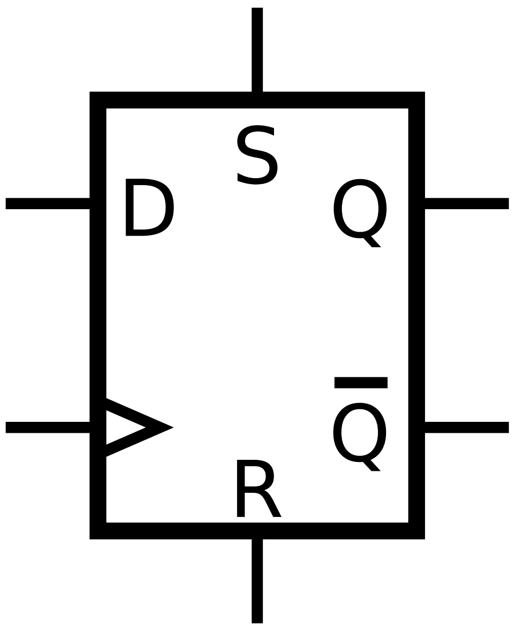
Earle latch uses complementary enable inputs: enable active low (E_L) and enable active high (E_H)

Earle latch The classic gated latch designs have some undesirable characteristics.[17] They require double-rail logic or an inverter. The input-to-output propagation may take up to three gate delays. The input-to-output propagation is not constant – some outputs take two gate delays while others take three.

Designers looked for alternatives.[18] A successful alternative is the Earle latch. It requires only a single data input, and its output takes a constant two gate delays. In addition, the two gate levels of the Earle latch can, in some cases, be merged with the last two gate levels of the circuits driving the latch because many common computational circuits have an OR layer followed by an AND layer as their last two levels. Merging the latch function can implement the latch with no additional gate delays.[17] The merge is commonly exploited in the design of pipelined computers, and, in fact, was originally developed by J. G. Earle to be used in the IBM System/360 Model 91 for that purpose.[19]

The Earle latch is hazard free.[20] If the middle NAND gate is omitted, then one gets the **polarity hold latch**, which is commonly used because it demands less logic.[20][21] However, it is susceptible to logic hazard. Intentionally skewing the clock signal can avoid the hazard.[21]

D flip-flop



D flip-flop symbol

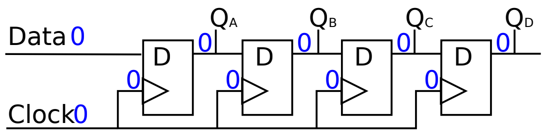
The D flip-flop is widely used. It is also known as a “data” or “delay” flip-flop.

The D flip-flop captures the value of the D-input at a definite portion of the clock cycle (such as the rising edge of the clock). That captured value becomes the Q output. At other times, the output Q does not change.[22][23] The D flip-flop can be viewed as a memory cell, a zero-order hold, or a delay line.[24]

Truth table:

('X' denotes a *Don't care* condition, meaning the signal is irrelevant)

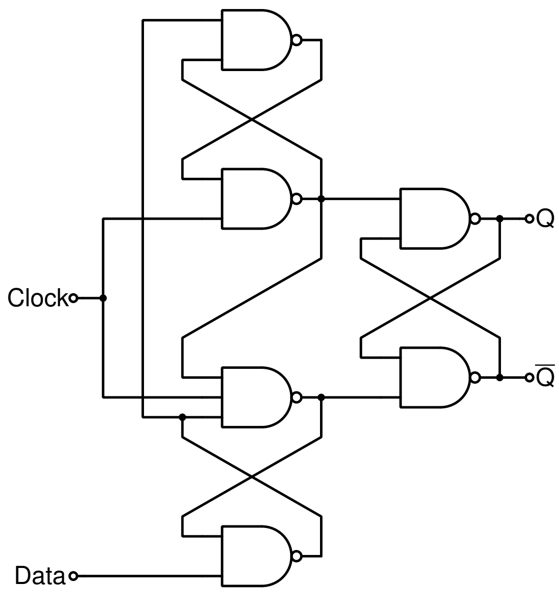
Most D-type flip-flops in ICs have the capability to be forced to the set or reset state (which ignores the D and clock inputs), much like an SR flip-flop. Usually, the illegal S = R = 1 condition is resolved in D-type flip-flops. By setting S = R = 0, the flip-flop can be used as described above. Here is the truth table for the others S and R possible configurations:



4-bit serial-in, parallel-out (SIPO) shift register

These flip-flops are very useful, as they form the basis for shift registers, which are an essential part of many electronic devices. The advantage of the D flip-flop over the D-type “transparent latch” is that the signal on the D input pin is captured the moment the flip-flop is clocked, and subsequent changes on the D input will be ignored until the next clock event. An exception is that some flip-flops have a “reset” signal input, which will reset Q (to zero), and may be either asynchronous or synchronous with the clock.

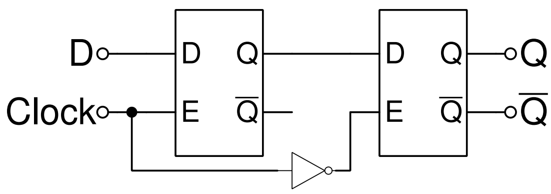
The above circuit shifts the contents of the register to the right, one bit position on each active transition of the clock. The input X is shifted into the leftmost bit position.



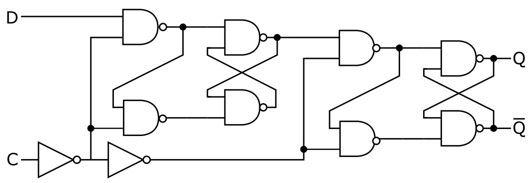
A positive-edge-triggered D flip-flop

Classical positive-edge-triggered D flip-flop This circuit[25] consists of two stages implemented by SR NAND latches. The input stage (the two latches on the left) processes the clock and data signals to ensure correct input signals for the output stage (the single latch on the right). If the clock is low, both the output signals of the input stage are high regardless of the data input; the output latch is unaffected and it stores the previous state. When the clock signal changes from low to high, only one of the output voltages (depending on the data signal) goes low and sets/resets the output latch: if D = 0, the lower output becomes low; if D = 1, the upper output becomes low. If the clock signal continues staying high, the outputs keep their states regardless of the data input and force the output latch to stay in the corresponding state as the input logical zero (of the output stage) remains active while the clock is high. Hence the role of the output latch is to store the data only while the clock is low.

The circuit is closely related to the gated D latch as both the circuits convert the two D input states (0 and 1) to two input combinations (01 and 10) for the output SR latch by inverting the data input signal (both the circuits split the single D signal in two complementary S and R signals). The difference is that in the gated D latch simple NAND logical gates are used while in the positive-edge-triggered D flip-flop SR NAND latches are used for this purpose. The role of these latches is to “lock” the active output producing low voltage (a logical zero); thus the positive-edge-triggered D flip-flop can also be thought of as a gated D latch with latched input gates.



A master–slave D flip-flop. It responds on the falling edge of the enable *input (usually a clock)*

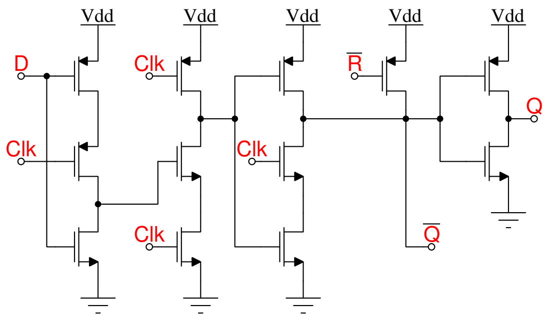


An implementation of a master–slave D flip-flop that is triggered on the rising edge of the clock

Master–slave edge-triggered D flip-flop A master–slave D flip-flop is created by connecting two gated D latches in series, and inverting the *enable* input to one of them. It is called master–slave because the second latch in the series only changes in response to a change in the first (master) latch.

For a positive-edge triggered master–slave D flip-flop, when the clock signal is low (logical 0) the "enable" seen by the first or "master" D latch (the inverted clock signal) is high (logical 1). This allows the "master" latch to store the input value when the clock signal transitions from low to high. As the clock signal goes high (0 to 1) the inverted "enable" of the first latch goes low (1 to 0) and the value seen at the input to the master latch is "locked". Nearly simultaneously, the twice inverted "enable" of the second or "slave" D latch transitions from low to high (0 to 1) with the clock signal. This allows the signal captured at the rising edge of the clock by the now "locked" master latch to pass through the "slave" latch. When the clock signal returns to low (1 to 0), the output of the "slave" latch is "locked", and the value seen at the last rising edge of the clock is held while the "master" latch begins to accept new values in preparation for the next rising clock edge.

By removing the leftmost inverter in the circuit at side, a D-type flip-flop that strobes on the *falling edge* of a clock signal can be obtained. This has a truth table like this:

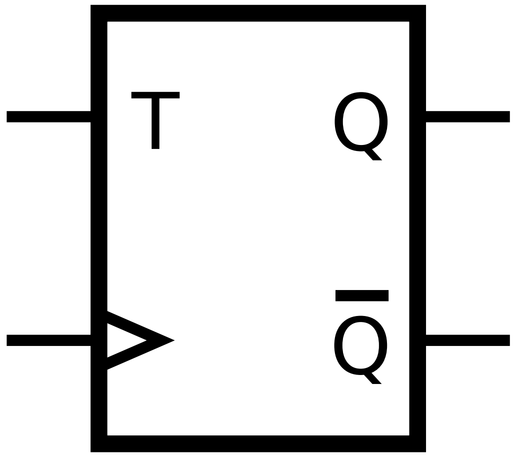


A CMOS IC implementation of a "true single-phase edge-triggered flip-flop with reset"

Edge-triggered dynamic D storage element An efficient functional alternative to a D flip-flop can be made with dynamic circuits (where information is stored in a capacitance) as long as it is clocked often enough; while not a true flip-flop, it is still called a flip-flop for its functional role. While the master–slave D element is triggered on the edge of a clock, its components are each triggered by clock levels. The "edge-triggered D flip-flop", as it is called even though it is not a true flip-flop, does not have the master–slave properties.

Edge-triggered D flip-flops are often implemented in integrated high-speed operations using dynamic logic. This means that the digital output is stored on parasitic device capacitance while the device is not transitioning. This design of dynamic flip flops also enables simple resetting since the reset operation can be performed by simply discharging one or more internal nodes. A common dynamic flip-flop variety is the true single-phase clock (TSPC) type which performs the flip-flop operation with little power and at high speeds. However, dynamic flip-flops will typically not work at static or low clock speeds: given enough time, leakage paths may discharge the parasitic capacitance enough to cause the flip-flop to enter invalid states.

T flip-flop



A circuit symbol for a T-type flip-flop

If the T input is high, the T flip-flop changes state ("toggles") whenever the clock input is strobed. If the T input is low, the flip-flop holds the previous value. This behavior is described by the characteristic equation:

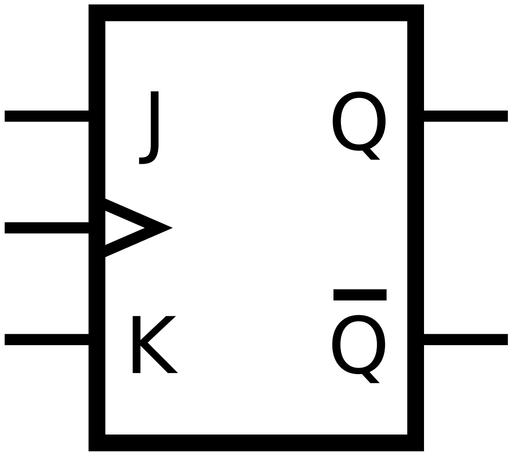
$Q_{\text{next}} = T \oplus Q = T\overline{Q} + \overline{T}Q$ (expanding the XOR operator)

and can be described in a truth table:

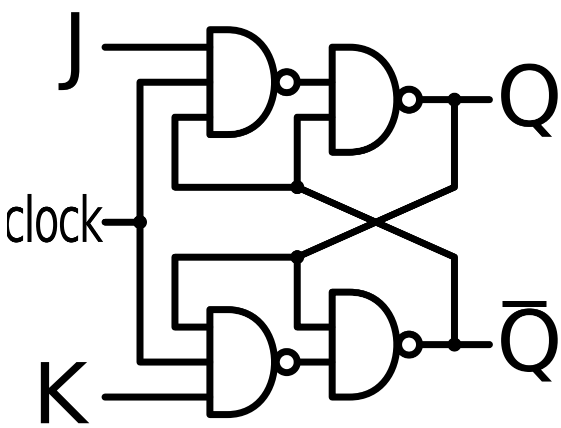
When T is held high, the toggle flip-flop divides the clock frequency by two; that is, if clock frequency is 4 MHz, the output frequency obtained from the flip-flop will be 2 MHz. This "divide by" feature has application in various types of digital counters. A T flip-flop can also be built using a JK flip-flop (J & K pins are connected together and act as T) or a D flip-flop (T input XOR Q_{previous} drives the D input).

JK flip-flop

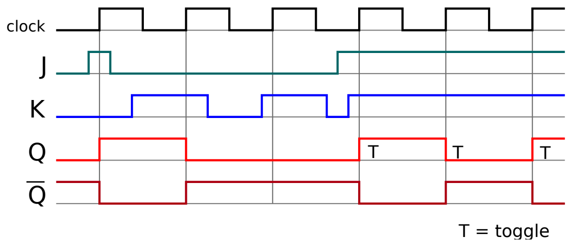
The JK flip-flop augments the behavior of the SR flip-flop (J=Set, K=Reset) by interpreting the J = K = 1 condition as a "flip" or toggle command. Specifically, the combination J = 1, K = 0 is a command to set the flip-flop; the combination J = 0, K = 1 is a command to reset the



A circuit symbol for a positive-edge-triggered JK flip-flop



A JK flip-flop made of NAND gates



JK flip-flop timing diagram

flip-flop; and the combination J = K = 1 is a command to toggle the flip-flop, i.e., change its output to the logical complement of its current value. Setting J = K = 0 maintains the current state. To synthesize a D flip-flop, simply set K equal to the complement of J. Similarly, to synthesize a T flip-flop, set K equal to J. The JK flip-flop is therefore a universal flip-flop, because it can be configured to work as an SR flip-flop, a D flip-flop, or a T flip-flop.

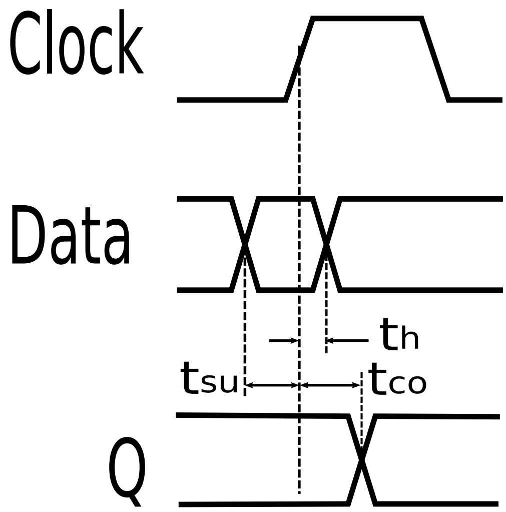
The characteristic equation of the JK flip-flop is:

$$Q_{\text{next}} = J\overline{Q} + \overline{K}Q$$

and the corresponding truth table is:

6.8.4 Timing considerations

Setup, hold, recovery, removal times



Flip-flop setup, hold and clock-to-output timing parameters

Setup time is the minimum amount of time a synchronous data input should be held steady **before** the clock event so that the data input is reliably sampled by the clock event.

Hold time is the minimum amount of time a synchronous data input should be held steady **after** the clock event so that the data input is reliably sampled by the clock event.

So to adhere to setup and hold times, a synchronous data input should be held steady from the setup time before the clock event to the hold time after the clock event.

Recovery time is the minimum amount of time an asynchronous set or reset input should be inactive **before** the clock event, so that the data input is reliably sampled by the clock, and thus not affected by the set or reset input.

Removal time is the minimum amount of time an asynchronous set or reset inputs should be held active **after** the clock event, so that the data is reliably controlled by the set or reset, and thus not affected by the data input.

So to adhere to recovery and removal times, an asynchronous set or reset input should be held steady from the recovery time before the clock event to the hold time after the clock event.

Short impulses applied to asynchronous inputs (set, reset) should not be applied completely within the recovery-removal period, or else it becomes entirely indeterminable whether the flip-flop will transition to the appropriate state. In another case, where an asynchronous signal simply makes one transition that happens to fall between the recovery/removal time, eventually the flip-flop will transition to the appropriate state, but a very short glitch may or may not appear on the output, dependent on the synchronous input signal. This second situation may or may not have significance to a circuit design.

Set and Reset (and other) signals may be either synchronous or asynchronous and therefore may be characterized with either Setup/Hold or Recovery/Removal times, and synchronicity is very dependent on the TTL design of the flip-flop.

Differentiation between Setup/Hold and Recovery/Removal times is often necessary when verifying the timing of larger circuits because asynchronous signals may be found to be less critical than synchronous signals. The differentiation offers circuit designers the ability to define the verification conditions for these types of signals independently.

Metastability

Main article: metastability in electronics

Flip-flops are subject to a problem called metastability, which can happen when two inputs, such as data and clock or clock and reset, are changing at about the same time. When the order is not clear, within appropriate timing constraints, the result is that the output may behave unpredictably, taking many times longer than normal to settle to one state or the other, or even oscillating several times before settling. Theoretically, the time to settle down is not bounded. In a computer system, this metastability can cause corruption of data or a program crash if the state is not stable before another circuit uses its value; in particular, if two different logical paths use the output of a flip-flop, one path can interpret it as a 0 and the other as a 1 when it has not resolved to stable state, putting the machine into an inconsistent state.[27]

The metastability in flip-flops can be avoided by ensuring that the data and control inputs are held valid and constant for specified periods before and after the clock pulse, called the **setup time** (t_{su}) and the **hold time** (t_h) respectively. These times are specified in the data sheet for the device, and are typically between a few nanoseconds and a few hundred picoseconds for modern devices. Depending upon the flip-flop's internal organization, it is possible to build a device with a zero (or even negative) setup or hold time requirement but not both simultaneously.

Unfortunately, it is not always possible to meet the setup and hold criteria, because the flip-flop may be connected to a real-time signal that could change at any time, outside the control of the designer. In this case, the best the designer can do is to reduce the probability of error to a certain level, depending on the required reliability of the circuit. One technique for suppressing metastability is to connect two or more flip-flops in a chain, so that the output of each one feeds the data input of the next, and all devices share a common clock. With this method, the probability of a metastable event can be reduced to a negligible value, but never to zero. The probability of metastability gets closer and closer to zero as the number of flip-flops connected in series is increased. The number of flip-flops being cascaded is referred to as the "ranking"; "dual-ranked" flip flops (two flip-flops in series) is a common situation.

So-called metastable-hardened flip-flops are available, which work by reducing the setup and hold times as much as possible, but even these cannot eliminate the problem entirely. This is because metastability is more than simply a matter of circuit design. When the transitions in the clock and the data are close together in time, the flip-flop is forced to decide which event happened first. However fast we make the device, there is always the possibility that the input events will be so close together that it cannot detect which one happened first. It is therefore logically impossible to build a perfectly metastable-proof flip-flop. Flip-flops are sometimes characterized for a maximum settling time (the maximum time they will remain metastable under specified conditions). In this case, dual-ranked flip-flops that are clocked slower than the maximum allowed metastability time will provide proper conditioning for asynchronous (e.g., external) signals.

Propagation delay

Another important timing value for a flip-flop is the clock-to-output delay (common symbol in data sheets: tCO) or propagation delay (tP), which is the time a flip-flop takes to change its output after the clock edge. The time for a high-to-low transition (tPHL) is sometimes different from the time for a low-to-high transition (tPLH).

When cascading flip-flops which share the same clock (as in a shift register), it is important to ensure that the tCO of a preceding flip-flop is longer than the hold time (t_h) of the following flip-flop, so data present at the input of the succeeding flip-flop is properly "shifted in" following the active edge of the clock. This relationship between tCO and t_h is normally guaranteed if the flip-flops are physically identical. Furthermore, for correct operation, it is easy to verify that the clock period has to be greater than the sum $t_{su} + t_h$.

6.8.5 Generalizations

Flip-flops can be generalized in at least two ways: by making them 1-of-N instead of 1-of-2, and by adapting them to logic with more than two states. In the special cases of 1-of-3 encoding, or multi-valued ternary logic, these elements may be referred to as *flip-flap-flops*.[28]

In a conventional flip-flop, exactly one of the two complementary outputs is high. This can be generalized to a memory element with N outputs, exactly one of which is high (alternatively, where exactly one of N is low). The output is therefore always a one-hot (respectively *one-cold*) representation. The construction is similar to a conventional cross-coupled flip-flop; each output, when high, inhibits all the other outputs.[29] Alternatively, more or less conventional flip-flops can be used, one per output, with additional circuitry to make sure only one at a time can be true.[30]

Another generalization of the conventional flip-flop is a memory element for multi-valued logic. In this case the memory element retains exactly one of the logic states until the control inputs induce a change.[31] In addition, a multiple-valued clock can also be used, leading to new possible clock transitions.[32]

6.8.6 See also

- Deadlock
- Latching relay
- Positive feedback
- Pulse transition detector

6.8.7 References

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6.8.8 External links

- FlipFlop Hierarchy, shows interactive flipflop circuits.
- The J-K Flip-Flop

Chapter 7

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White, Chewbacca01, Icep, Mlađa, AntiVandalBot, Wang ty87916, Opelio, Jwhamilton, Minhtung91, Arthurmyles, JAnDbot, Husond, Wiki0709, Andonic, SteveSims, Bongwarrior, VoABot II, Roger2909, Romtobbi, Indon, Nposs, 28421u2232nfenfcenc, DerHexer, Khalid Mahmood, InvertRect, MartinBot, BetBot~enwiki, Burnedthru, R'n'B, Kateshortforbob, CommonsDelinker, AlexiusHoratius, Ash, J.delanoy, Littletemchin, Madadem, Trusilver, Geomanjo, DigitalCatalyst, M C Y 1008, Nemo bis, Hillock65, Scoobystones, Hut 6.5, NewEnglandYankee, Potatoswatter, Cometstyles, RB972, Treisijs, Inter16, Pdcook, Lseixas, SoCalSuperEagle, Mlewis000, Sheliak, Deor, ABF, LokiClock, Constant314, Philip Trueman, The Original Wildbear, Mikethorny, Ekwonderland, Seraphim, Martin451, Psyche825, Venny85, Andy Dingley, Yk Yk Yk, Enviroboy, Purgatory Fubar, Spinningspark, Big G Ursa, Gallagher69, NHRHS2010, Bernmaster, SieBot, Coffee, K. Annoyomous, Msadaghd, GrooveDog, Bentogoa, JD554, Paolo.dL, Faradayplank, Poindexter Propellerhead, Svick, Dcook32p, Anchor Link Bot, WikiLaurent, BentzyCo, DRTllbrg, ClueBot, Fribbler, GorillaWarfare, MacroDaemon, Mild Bill Hiccup, Richerman, Delta1989, No such user, Jusdafax, Abhirocks94, Gtstricky, Lartoven, Promethean, Gciriani, Yadvinder, Wisewarlock, Glen Chagrin, Jfioeawfjdls453, Subash.chandran007, Versus22, Meske, Lxmota, SoxBot III, RMFan1, PatrickBogdziewicz, Rror, Ahirwav, Alexius08, Noctibus, JinJian, Thatguyflint, Cxz111, Willking1979, Manuel Trujillo Berges, Some jerk on the Internet, Sceny, Hda3ku, Fgnievinski, MoysieGT, Gizza gander, SoSaysChappy, LaaknorBot, Chamal N, Glane23, Chzz, 5 albert square, Naidevinci, Ehrenkater, Tide rolls, Lightbot, PRRP, Secundus Zephyrus, Bmendonc, Megaman en m, Legobot, Luckas-bot, Yobot, Niklo sv, CinchBug, Tempodivalse, Cnorrisindustry, Orion11M87, AnomieBOT, KDS4444, Killiondude, Jim1138, AdjustShift, Dr. Pathos, RandomAct, Materialscientist, Carlsotr, Raven1977, Xqbot, Athabaska-Clearwater, Capricorn42, SchfiftyThree (Public), Jeffrey Mall, GrouchoBot, Cooltoad4102, Trurle, Oli19, Karlmossmans, JulianDelphiki, Shadowjams, Mike Dill~enwiki, Erik9, ??, Bekus, GliderMaven, Prari, FrescoBot, Pepper, Wikipe-tan, Sky Attacker, Citation bot 1, Pinethicket, Flekstro, Tinton5, Jusses2, Var0017, Serols, Mak2109, Meaghan, Robo Cop, Turian, Malikserhan, December21st2012Freak, IVAN3MAN, TobeBot, Heyyyyah, SchreyP, Jonkerz, Lotje, Defender of torch, Specs112, Michael.goulais, PleaseStand, Systemdweller, Jo big daddy, TjBot, 123Mike456Winston789, Mandolinface, EmausBot, John of Reading, Acather96, Gfoley4, GoingBatty, I am from south wales, Tommy2010, Netheril96, Wikipelli, AvicBot, JSquish, Fæ, Josve05a, Imperial Monarch, Gdaman5, Dondervogel 2, Pokeyclap7, Stephen C Wells, Newlen, Lambrosus, Jsayre64, Rseagull, ChuispastonBot, RockMagnetist, Teapeat, DASHBotAV, Kj13isaac, Xonqnopp, ClueBot NG, Gilderien, Benydogc13, Enopet, Rezabot, ThatAMan, Helpful Pixie Bot, Wbm1058, Lowercase sigmabot, Hallows AG, Metricopolus, Mark Arsten, Cj3975, Shawn Worthington Laser Plasma, OSU1980, Vanished user lt94ma34le12, Neshmick, ChrisGualtieri, GoShow, Embrittled, Garamond Lethe, SoledadKabocha, Tabrin-mabra, IWikileaks, Kyohyi, JohnnyJones1018, Dustin V. S., Flat Out, Tigraan, Spyglasses, Ducksandwich, Vavdeev, Grammato, Monkbot, Quantumofthought, Pulkitmidha, Non-pupulus-impilium, Shubham bhardwaj btp, KasparBot, MrArsGravis, Bubbagump1234, Cirris Systems, Howager, Sarthakniar and Anonymous: 732

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- **Passivity (engineering)** *Source:* https://en.wikipedia.org/wiki/Passivity_(engineering)?oldid=708784594 *Contributors:* The Anome, Heron, RTC, Michael Hardy, RickK, Omegatron, TedPavlic, Hooperbloob, KAWASAKI Hiroyuki, Cbdorsett, GregorB, Isnow, BD2412, Ordinary K, Casey Abell, Lugnad, Mike Segal, Nimur, YurikBot, Toffile, Jpbowen, EAderhold, SmackBot, WookieInHeat, Jibjibjib, Lindosland, DHN-bot~enwiki, Hkmaly, SashatoBot, CapitalR, Chetvorno, Cydebot, Thijs!bot, JAnDbot, R'n'B, Ahzahraee, Iverson2, TXiKiBoT, Riick, Spinningspark, Alcmaeonid, AlleborgoBot, Pmitros, Alexbot, Elcap, WikHead, Addbot, Numbo3-bot, JB Gnome, Pietrow, Luckas-bot, Yobot, Grebaldar, AnomieBOT, Ciphers, Dinesh smita, SvartMan, Citation bot, Phluid61, RibotBOT, Maitchy, Steve Quinn, Citation bot 1, Jonesey95, Trappist the monk, Clarkcj12, Jovargh, ClueBot NG, Helpful Pixie Bot, Monkbot, Mpj7 and Anonymous: 50
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- **RLC circuit** *Source:* https://en.wikipedia.org/wiki/RLC_circuit?oldid=705075880 *Contributors:* Waveguy, Heron, Patrick, Glenn, Reddi, Omegatron, Tonsofpcs, Giftlite, Wolfkeeper, Jorend, ILUsion~enwiki, Rich Farmbrough, Sam Derbyshire, MisterSheik, CanisRufus, Hooperbloob, Wtshymanski, RJFJR, Gene Nygaard, Alai, BillC, Jeff3000, Tabletop, Isnow, Eyreland, Pfalstad, Marudubshinki, Msiddalingaiah, Graham87, BD2412, Arabani, Klassykittychick, HappyCamper, Erkcan, Gsp, Arnero, Alfred Centauri, Fresheneesz, Alphachimp, Bgwhite, EricCHill, YurikBot, Bamgooly, BOT-Superzerocool, Light current, KNfLrPnKNsT, Rdrosson, SmackBot, Sagie, Bluebot, AhmedHan, Metacomet, DHN-bot~enwiki, Gruzd, Ryouko, Kbwikipedia, Doodle77, Sammy1339, DJIndica, HeroTsai, Stufam, Aleator, Aleenf1, ErikHK~enwiki, Profjohn, Tawkerbot2, Chetvorno, Kurtan~enwiki, DumbBOT, Jrgetsin, Optimist on the run, Thijs!bot, Siwiak, JAnDbot, CosineKitty, Lidnariq, Bubba hotep, First Harmonic, Scumbagoldhag, Woutput, Pharaoh of the Wizards, Kar.ma, Fountains of Bryn Mawr, Mlewis000, Bestproofreader, Philip Trueman, TXiKiBoT, Oshwah, The Original Wildbear, Caster23, Tsi43318, Ilyushka88, Pinin~enwiki, Spinningspark, Monty845, LordEniac, Kbrose, Robket, MinorContributor, Czap42, ClueBot, Wolfch, Thegeneralguy, Green

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- **Low-pass filter** *Source:* https://en.wikipedia.org/wiki/Low-pass_filter?oldid=708280186 *Contributors:* Mav, The Anome, Rjstott, Heron, Patrick, JohnOwens, Lexor, David Martland, Glenn, Palfrey, Dysprosia, Furrykef, Omegatron, ThereIsNoSteve, Giftlite, DavidCary, Wolfkeeper, BenFrantzDale, Bensaccount, Vadmium, LucasVB, Antandrus, BrianWilloughby, Moxfyre, Rfl, Rich Farmbrough, TedPavlic, Mecanismo, ESkog, Teorth, Foobaz, Cavrdg, Hangjian, Hooperbloob, Dragoljub, Wtshymanski, Cburnett, Flying fish, Davidkazuhiro, Pol098, Akavel~enwiki, Pfalstad, Torquil~enwiki, Mikm, Alfred Centauri, Kri, Krishnavedala, Borgx, PinothyJ, Toffile, Gaius Cornelius, Brandon, Mikeblas, Searchme, Light current, Mickpc, Deville, Petri Krohn, LeonardoRob0t, Phil Holmes, RG2, Mejor Los Indios, EXonyte, KnightRider~enwiki, Mitchan, Steve carlson, Pgk, Niehaus~enwiki, ASarnat, Chris the speller, Nbarth, RoysonBobson, Zvar, Soundsop, IE, P.o.h, Elzair, Dog Eat Dog World, Minna Sora no Shita, Rogerbrent, Dicklyon, Kvng, Ss181292, Unmitigated Success, Myasuda, Paddles, Editor at Large, Epbr123, Sobreira, Bobblehead, Brichcja, Majorly, Danroa, Lovibond, Ekkanant, JAnDbot, Xhienne, Drizzd~enwiki, Time3000, Bongwarrior, VoABot II, Dics, Eus Kevin, Parijata, Kayau, MartinBot, Renski, Tgeairn, RockMFR, Mange01, Slamedsilver, LLcopp, VolkovBot, Inductiveload, Ahmedsaieed, Spinningspark, Anoko moonlight, Kbrose, Tetos~enwiki, Tugjob, Dp67, ClueBot, Binksternet, Brews ohare, Thingg, 7, Dusen189, Johnuniq, XLinkBot, Mm40, ZooFari, Addbot, Howard Landman, Jojhutton, Redheylin, Parvejkhan, Nocal, Tide rolls, Gail, Legobot, Bdb112, Yobot, AnomieBOT, Floquenbeam, Jim1138, B137, Materialscientist, Citation bot, Xqbot, Armstrong1113149, Pontificalibus, Christopherley, RibotBOT, Rb88guy, Hlovatt, GliderMaven, ICEAGE, Jonesey95, RedBot, Piandcompany, December21st2012Freak, Trappist the monk, The Utahraptor, Mgclapé, Astro89, WikitanvirBot, Immunize, Dewritech, Catshome2000, Clusternote, Zueignung, Teapeat, Dweymouth, ClueBot NG, Satellizer, Widr, BG19bot, Varun varshney12, OceanEngineerRI, Kizzlebot, JYBot, Kroq-gar78, CsDix, Babitaarora, My name is not dave, Quenhitran, Meteor sandwich yum, Monkbot, Andars97 and Anonymous: 236
- **High-pass filter** *Source:* https://en.wikipedia.org/wiki/High-pass_filter?oldid=686068484 *Contributors:* The Anome, Rjstott, Pierre-Abbat, Lexor, Glenn, Charles Matthews, Omegatron, Eugene van der Pijll, ThereIsNoSteve, Tonsofpcs, BenFrantzDale, Vadmium, Rfl, TedPavlic, Bobo192, Rbj, Foobaz, Hooperbloob, Dragoljub, RJFJR, Zawersh, Gene Nygaard, Bruce89, Thryduulf, Robert K S, GregorB, Waldir, Pfalstad, Rjwilmsi, Lockley, Arnero, PinothyJ, Alynna Kasmira, Mikeblas, Attilios, KnightRider~enwiki, SmackBot, Chris the speller, Vina-iwbot~enwiki, P.o.h, Elzair, Soumyasch, Dicklyon, Shaunwhite000, Shoez, Myasuda, Scoofy, Sobreira, Dalahäst, Drizzd~enwiki, AndyBloch, .anacondabot, Magioladitis, Faizhaider, Baccyak4H, Katalaveno, Joerglwitsch, Ziounclesi, Spinningspark, Kbrose, Tresiden, Fibo1123581321, Jojalozzo, Bekuletz, ClueBot, Binksternet, Estirabot, Gciriani, XLinkBot, Addbot, Jojhutton, Olli Niemitalo, Download, Redheylin, Legobot, Yobot, Fraggle81, Amirobot, EnTerr, Gianno~enwiki, Citation bot, ShornAssociates, Armstrong1113149, RibotBOT, Mnmngb, Maitchy, Ll1324, JMS Old Al, Toriicelli, DARTH SIDIOUS 2, EmausBot, Xiutwel-0003, ChuispastonBot, ClueBot NG, Rezabot, Helpful Pixie Bot, Gfoltz9, AvocatoBot, ChrisGualtieri, Txnhockey3, CsDix, Babitaarora, The Herald, Monkbot, BU Rob13, Shriniketh91 and Anonymous: 87
- **Band-pass filter** *Source:* https://en.wikipedia.org/wiki/Band-pass_filter?oldid=689838056 *Contributors:* The Anome, Maury Markowitz, Patrick, Angela, Nanobug, Glenn, Poor Yorick, BAxelrod, Emmjade, Guaka, Omegatron, ThereIsNoSteve, Giftlite, Sword~enwiki, Zowie, Rfl, CALR, Billlion, Shanes, Hooperbloob, SidP, Cburnett, OwenX, Cbdorsett, Pfalstad, Zbxgscqf, Sango123, Ianthegecko, Arnero, Antikon, DVdm, Martin Hinks, YurikBot, Splash, PinothyJ, Toffile, Brandon, Hakeem.gadi, Deville, KNfLrPnKNsT, LeonardoRob0t, Poulpy, Machtzu, RG2, Henrikb4, Binarypower, Commander Keane bot, Oli Filth, Vina-iwbot~enwiki, Clicketyclack, Robofish, Mofomojo, Dicklyon, Tawkerbot2, Nalvage, Sobreira, AlienBlancmange, CosineKitty, Email4mobile, RisingStick, STBot, Mange01, Acalamari, VolkovBot, Cuddlyable3, Inductiveload, Spinningspark, Benjwgarner, Dp67, Binksternet, PipepBot, ChrisHodgesUK, Johnuniq, Addbot, Alexandra Goncharik, Redheylin, OlEnglish, B137, Citation bot, GrouchoBot, GliderMaven, Ebrambot, Lorem Ip, ClueBot NG, Rezabot, Helpful Pixie Bot, Flyguy53, Ankitd.elec, Chetan.meshram, Omegaoptical, Forestrf, CsDix, Ugog Nizdast, Trackteur, Wikigeek244, Joshua Mahesh Inayathullah and Anonymous: 67
- **P–n junction** *Source:* https://en.wikipedia.org/wiki/P%E2%80%93n_junction?oldid=707366863 *Contributors:* AxelBoldt, Waveguy, RTC, Dmd3e, Mac, Glenn, HolIgor, Auric, Wjbeaty, Ancheta Wis, Rafaelgr, Armandino, Mako098765, Abdull, Jfraser, Matt Britt, Foobaz, Timl, Storm Rider, Eric Kvaalen, Keenan Pepper, Wtshymanski, Tebbb, Marudubshinki, Nanite, Amr Ramadan, Vegaswikian, LjL, Prgo, Alfred Centauri, Kolbasz, Tomer Ish Shalom, Chobot, YurikBot, Sceptre, Gaius Cornelius, Shaddack, NawlinWiki, Bota47, Kkmurray, Light current, Chaiken, Katieh5584, Attilios, SmackBot, Jacek Kendysz, Mauls, JAn Dudík, Bluebot, Pieter Kuiper, MalafayaBot, Darth Panda, Apocryphite, Radagast83, Drphilharmonic, DMacks, Catani~enwiki, Vriullop, Intellectnfun, JorisvS, CyrilB, Vanished user 8ij3r8jwefi, Dicklyon, Filelakeshoe, Chetvorno, SkyWalker, Rowellcf, Christian75, Maque~enwiki, Thijs!bot, Headbomb, Electron9, Gerry Ashton, AntiVandalBot, Email4mobile, Dukebody, Kskowron, Gresszilla, TheNoise, MartinBot, Bissinger, Glrx, CommonsDelinker, Mintz l, LordAnubisBOT, NewEnglandYankee, Cmichael, DorganBot, PowerWill500, VolkovBot, Larryisgood, Scholzilla, Someguy1221, Lerdthenerd, Andy Dingley, AlleborgoBot, Nagy, SieBot, VVVBot, Delu 85, Pratik mallya, Nopetro, Wilson44691, Arjen Dijksman, Siyamraj, Anchor Link Bot, ClueBot, Brews ohare, Vboo-belarus, XLinkBot, Terry0051, MystBot, Zinger0, Addbot, Mortense, Napy1kenobi~enwiki, ProperFraction, Download, Jamesrei, Shrikul joshi, ScAvenger, Cesaar, Luckas-bot, Yobot, Senator Palpatine, Choij, Materialscientist, Citation bot, Darcovian, DSisyphBot, Igorpark, Raffamaiden, Rickproser, Jangirke, FrescoBot, Jc3s5h, BenzolBot, Kevin-Cox, I dream of horses, MJ94, SpaceFlight89, Lowrybob, Javaidphy, علی ویکی, TheGrimReaper NS, MrSnoot, Bhawani Gautam, EmausBot, Beatnik8983, Dewritech, Monterey Bay, TyA, Xiutwel-0003, Noophilic, ClueBot NG, Starshipenterprise, Jbolte, Widr, Helpful Pixie Bot, Wbm1058, Helloakshaypoddar, Metricopolus, Satishb.elec, Tarunselec, Ulidtko, Cyberbot II, C susil, Aloysius314, IngenieroLoco, Rfassbind, Ginsuloft, TooOldMan, Mattkevmd, Jadecatz, Erprabhatjani, Kirasan5, Crystallizedcarbon, KasparBot, Hugo, Goodphy, Ankurg92 and Anonymous: 198
- **Bipolar junction transistor** *Source:* https://en.wikipedia.org/wiki/Bipolar_junction_transistor?oldid=709181580 *Contributors:* AxelBoldt, Sandos, Mudlock, Heron, RTC, Michael Hardy, Tim Starling, Ahoerstemeier, Kaeslin, Glenn, Stefan-S, Nikai, Dcoetzee, The Anomebot, Maximus Rex, Omegatron, Josh Cherry, Jondel, Giftlite, Christopher Parham, DavidCary, Mat-C, MathKnight, Everyking, Leonard G., Micru, Vadmium, Chowbok, Utcursch, Mako098765, Rich Farmbrough, TedPavlic, Pjacobi, Kbh3rd, Plugwash, Sfahey, Bdieseldorff, Rgdboer, Bookofjude, Smalljim, Matt Britt, Hooperbloob, Alansohn, RobertStar20, Pion, Wtshymanski, Dirac1933, Gene Nygaard, Capecodeph, Dan100, Kenyon, Unixxx, Kfitzner, Mário, Jftsang, Pink-isnt-well, Lincher, CPES, Graham87, Yurik, Pharlap, Nanite, Snafflekid, Rjwilmsi, DonSiano, Lor772, FlaBot, Ian Pitchford, Arnero, Alfred Centauri, Nimur, Fresheneesz, Physchim62, Jidan,

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- **Amplifier** *Source:* https://en.wikipedia.org/wiki/Amplifier?oldid=708723581 *Contributors:* AxelBoldt, Eloquence, Mav, Ray Van De Walker, SimonP, Waveguy, Heron, Kku, Ixfd64, Delirium, Docu, Kingturtle, Glenn, Nikai, GRAHAMUK, Jengod, Ww, Wik, Jessel, Maximus Rex, Omegatron, Bevo, Raul654, Lumos3, Friedo, RedWolf, Donreed, Dave Bass, Hcheney, David Gerard, Centrx, Giftlite, DocWatson42, Lunkwill, DavidCary, Laudaka, Lupin, Vk2tds, Markus Kuhn, Jcobb, AJim, Maroux, Jason Quinn, Nayuki, Wmahan, Chowbok, Sam Hocevar, Jcorgan, BrianWilloughby, Abdull, Rich Farmbrough, TedPavlic, Guanabot, Pmsyyz, Pt, Meggar, Timl, Hooperbloob, Watsonladd, Malo, Osmodiar, Wtshymanski, Twisp, Crosbiesmith, Woohookitty, Uncle G, Pol098, Peter Beard, DaveApter, BD2412, FreplySpang, Snafflekid, Koavf, Amire80, Quiddity, Oblivious, Brighterorange, RobertG, Arnero, Margosbot~enwiki, Alfred Centauri, Kolbasz, Krishnavedala, 121a0012, Bgwhite, Ahpook, The Rambling Man, Nol Aders, Matt512, Epolk, Bergsten, Chaser, Rohitbd, Bjf, Bou, Welsh, Howcheng, Thiseye, Dhollm, Speedevil, DeadEyeArrow, Searchme, Light current, Mattg2k4, Deville, Kungfuadam, Mebden, Jer ome, Kf4bdy, Kimdino, SmackBot, Reedy, Unyoyega, Freestyle~enwiki, Daviddavid, Lindosland, Amatulic, Chris the speller, Bluebot, TimBentley, Cadmium, Jprg1966, Thumperward, Papa November, Szidomingo, Sajendra, OrphanBot, Seduisant, Evilspoons, SnappingTurtle, DMacks, Pilotguy, Bn, Shields020, Breno, Minna Sora no Shita, CyrilB, Rogerbrent, Dicklyon, 2006mba, Kvng, Politepunk, OnBeyondZebrax, Iridescent, Lumos3, Walton One, Mihitha, Yves-Laurent, Chetvorno, JohnTechnologist, Xcentaur, CmdrObot, Chrumps, Nczempin, Lenilucho, Anoneditor, Doctormatt, Tubenutdave, Red Director, HermanFinster, Australian audio guy, FredYork, Gionnico, Editor at Large, Enter The Crypt, Pjvpjv, Saimhe, Guy Macon, Mccartyp, Lovibond, CPMartin, Lbecque, Esmond.pitt, CombatWombat42, CosineKitty, TAnthony, MegX, Jahoe, Xoneca, Magioladitis, VoABot II, Askari Mark, JNW, JamesBWatson, Faizhaider, MichaelSHoffman, Black Stripe, Ngwill, MartinBot, Sigmundg, Jim.henderson, Anaxial, Nono64, Masisnr1, M samadi, DrKay, AntiSpamBot, SophieCat, Vspengen, Colorbow, Ale2006, Mlewis000, Funandtrvl, Joeinwap, Meiskam, ICE77, Philip Trueman, Oshwah, The Original Wildbear, Zuperman~enwiki, Smcreator, Henrydask~enwiki, Anonymous Dissident, Afluent Rider, Someguy1221, Monkey Bounce, Don4of4, Jackfork, Billinghurst, Kilmer-san, Dragonkillernz, Spinningspark, Internetexploder, Biscuittin, Audioamp, Jokullmusic, Krawi, Kotabatubara, Hiddenfromview, Henry Delforn (old), Lightmouse, Nitram cero, StaticGull, Denisarona, Asher196, Thinkingatoms, ClueBot, Binksternet, The Thing That Should Not Be, GeoffreyHale, Jan1nad, Wysprgr2005, GreenSpigot, AnnArborRick, Niceguyedc, Blanchardb, Linan0827, Gtstricky, Brews ohare, Arjayay, Versus22, Johnuniq, XLinkBot, Alexius08, Revancher, Srcloutier, Pedro magalhaes86, Addbot, Mortense, Olli Niemitalo, Fgnievinski, Avobert, Yobot, Jordsan, Bestiasonica, Dleger, P1ayer, Sarukum, AnomieBOT, Piano non troppo, B137, Materialscientist, Citation bot, LilHelpa, Justanothervisitor, Harikrishna69, Ubcule, Maitchy, Uusijani, GliderMaven, FrescoBot, Gog182, Jc3s5h, Nickw2066, Nojiratz, Gdje je nestala duša svijeta, Icontech, I dream of horses, TechnoDanny, Anooshg, Jujutacular, Hessamnia, Orenburg1, Theo10011, Belledonne, Qianchq, John of Reading, Kodabmx, Cmavr8, Dewritech, TuomTuo, GoingBatty, Solarra, AnonymousNarrator, The Nut, ChunkyPastaSauce, Namoroka, Tuborama, Peterh5322, Lowkyalur, Jefffolly, Lakkasuo, Nikolas Ojala, Petrb, ClueBot NG, Jaanus.kalde, MelbourneStar, This lousy T-shirt, Piast93, Andreas.Persson, Historikeren, Robsuper, MerlIwBot, Helpful Pixie Bot, HMSSolent, Bibcode Bot, Supersam654, CitationCleanerBot, 1292simon, Braun walter, ChrisGualtieri, Ajv39, Dexbot, SoledadKabocha, Frosty, Mark viking, Epicgenius, Acrislg, I am One of Many, Jamesmcmahon0, Brzydalski, Spyglasses, Rewa, AddWittyNameHere, Stamptrader, JaconaFrere, Jbolton07, Gerbenvaneerten, Barefootwhistler, MasterTriangle12, Grsh90, Kennellm, Anupambharti1995, Paulinaacuna, Sweepy, Santoshjain000, G-dac and Anonymous: 433
- **Operational amplifier** *Source:* https://en.wikipedia.org/wiki/Operational_amplifier?oldid=707203474 *Contributors:* Mav, The Anome, WillWare, Malcolm Farmer, Heron, Edward, RTC, Michael Hardy, Mahjongg, Wapcaplet, Julesd, Glenn, Ghewgill, GRAHAMUK, Bemoeial, Dysprosia, Andrewman327, Omegatron, Wernher, AnonMoos, AlexPlank, Hankwang, RedWolf, Donreed, Smither, Pengo, Giftlite, DavidCary, Mintleaf~enwiki, Inkling, Ds13, CyborgTosser, Leonard G., Frencheigh, Rpyle731, Mboverload, Foobar, Mike R, Aulis Eskola, DRE, Eranb, KeithTyler, Clemwang, M1ss1ontomars2k4, Adashiel, TedPavlic, ArnoldReinhold, Sn0wflake, ESkog, Plugwash, Dpotter, CanisRufus, Bdieseldorff, Shanes, Bobo192, Nigelj, .:Ajvol:., Foobaz, Hooperbloob, Musiphil, Neonumbers, Atlant, Keenan Pepper, Wtmitchell, Wtshymanski, Gene Nygaard, Alai, DSatz, Unixxx, Weyes, Woohookitty, Mindmatrix, Pol098, Cbdorsett, CPES, Gimboid13, Cataclysm, Msiddalingaiah, Snafflekid, Bvankuik, Sjakkalle, Arabani, Alejo2083, Chris Pressey, Ground Zero, Margosbot~enwiki, Efficacy, Alfred Centauri, RexNL, Enon, Fresheneesz, Srleffler, Bgwhite, YurikBot, Borgx, Gaius Cornelius, Rohitbd, Synaptidude, Grafen, 48v, Sparkinark, TDogg310, Voidxor, Supten, DeadEyeArrow, Jeh, Elkman, Kkmurray, Searchme, Bakkster Man, Light current, Super Rad!, Closedmouth, Mike1024, Mebden, Luk, Peranders, SmackBot, Igtorque, Thelukeeffect, Speight, Man with two legs, Jwestbrook, Yamaguchi??, Gilliam, Lindosland, QEDquid, KD5TVI, Chris the speller, Bluebot, Oli Filth, EncMstr, Papa November, DHN-bot~enwiki, FredStrauss, Audriusa, Royboycrashfan, Can't sleep, clown will eat me, LouScheffer, CanDo, TWINE006, Henning Makholm, Evlekis, Bejnar, Ohconfucius, Missamo80, Archimerged, Awbliven, JohnWittle, Antireconciler, CyrilB, Rogerbrent, Dicklyon, Novangelis, Kvng, Pgadfor, Yves-Laurent, Chetvorno, Phil Christs, JForget, Circuit dreamer, NickW557, WeggeBot, Myasuda, Anoneditor, Naspilot, Pyrilium, ZHENG Jiajun, Viscious81, HermanFinster, Christian75, Khattab01~enwiki, Raidfibre, Josemiotto, Editor at Large, Saintrain, Serych, Barticus88, Sunny sin2005, Electron9, Vasurak, Jonnie5, Nick Number, Escarbot, AntiVandalBot, Luna Santin, Seaphoto, Lovibond, MikeLynch, JAnDbot, .K, CosineKitty, Magioladitis, Secret Squïrrel, Acu7, Somebody2014, Hypergeek14, Swift-

Bot, Clankypup, Crunchy Numbers, First Harmonic, Allstarecho, Nodekeeper, Cocytus, Manavbhardwaj, Mårten Berglund, Sigmundg, Glrx, CommonsDelinker, Jascii, J.delanoy, Jcurie, Sakthivel30, Zen-in, Szzuk, SJP, Rumpelstiltskin223, TottyBot, Homer Landskirty, Pmoseley, Red Thrush, VolkovBot, ICE77, Philip Trueman, DoorsAjar, Draurbilla, Ianr44, Bizarro Bull, Inductiveload, Andy Dingley, Spinningspark, SieBot, Caltas, Charles.small, Roy hu, Jjwilkerson, Jp314159, Opamp, Bentogoa, M Puddick, OsamaBinLogin, Evaluist, Faradayplank, PHermans, OscarJuan, PerryTachett, ClueBot, Smart Viral, Binksternet, Helenabella, ArthurOgawa, Mild Bill Hiccup, Srinivasbt, Alexbot, Jusdafax, Brews ohare, Sldghmmr, La Pianista, Wstorr, Aitias, Johnuniq, SoxBot III, Analogkidr, Salam32, Alexius08, ZooFari, Skonieczny, Gggh, Addbot, Mortense, Some jerk on the Internet, Olli Niemitalo, Theleftorium, Sudeepa123, Ppj4, Download, Punkguitar, AnnaFrance, Favonian, LinkFA-Bot, Bruno gouveia rodrigues, Supav1nnie, Eng general, OlEnglish, Pietrow, Zorrobot, RobertTanzi, Luckas-bot, Yobot, Ptbotgourou, Annomination, AnomieBOT, Paulthomas2, Jim1138, JackieBot, Piano non troppo, LiuyuanChen, Materialscientist, Citation bot, Akilaa, Xqbot, Sellyme, XZeroBot, ادقولا, Dprabhu, Maitchy, Endothermic, GliderMaven, FrescoBot, LucienBOT, Ong saluri, Berrinkursun, Anitauky, Wikigayburgers, Roman12345, Vhann, Gdje je nestala duša svijeta, I dream of horses, Jonesey95, Hoo man, Ezhuttukari, Mikespedia, Abhishekchavan79, Æneas, Dinamik-bot, Overjive, PleaseStand, DARTH SIDIOUS 2, Teravolt, Breezeboy, EmausBot, John of Reading, Kasper Meerts, Torturella, Tawsifkhan, Solarra, Meht7860, Dcirovic, Fæ, East of Borschov, Aflafla1, Thine Antique Pen, Rcsprinter123, Sbmeirow, Peterh5322, L Kensington, Danielop-NJITWILL, VictorianMutant, Petrb, Sudheerp99, ClueBot NG, Jaanus.kalde, This lousy T-shirt, Grottolese, Ulrich67, Muon, Iinvnt, Widr, Lain.cai, Oddbodz, Helpful Pixie Bot, Wbm1058, Czar44, Tony Tan, SodaAnt, Minsbot, Analogueic, Yogirox234, Hghyux, MarinSwimmer, Cyberbot II, ChrisGualtieri, SD5bot, Dexbot, Jamesx12345, Visitor01, Babitaarora, Monkbot, Pcrengnr, TerryAlex, MorganBEAST, AntonKruger-AtUiowa, Madphysics, 6965REHAN, Sopogupta, KasparBot, “Chipotle” is NOT pronounced “chi-POL-tay"!, Sweepy, The Manic Puppeteer, Fyi2357, SSTflyer, Balaji balai, Kdeepakkk, Colonel abrar and Anonymous: 498

- **Boolean algebra (logic)** *Source:* https://en.wikipedia.org/wiki/Boolean_algebra?oldid=709143682 *Contributors:* William Avery, Michael Hardy, Dan Koehl, Andrewa, Tacvek, Hyacinth, Tobias Bergemann, Thorwald, Paul August, Bender235, ESkog, EmilJ, Gary, Wtmitchell, Oleg Alexandrov, Mindmatrix, Michiel Helvensteijn, BD2412, Rjwilmsi, Pleiotrop3, Jrtayloriv, Rotsor, Wavelength, Hairy Dude, Trovatore, MacMog, StuRat, Arthur Rubin, Caballero1967, Sardanaphalus, SmackBot, Incnis Mrsi, Gilliam, Tamfang, Lambiam, Wvbailey, Khazar, Iridescent, Ghaly, Vaughan Pratt, CRGreathouse, CBM, Neelix, Gregbard, QuiteUnusual, Magioladitis, David Eppstein, Tony-Brooke, Glrx, Pomte, BaseballDetective, Jmajeremy, Nwbeeson, Izno, JohnBlackburne, Tavix, BotKung, PericlesofAthens, CMBJ, SieBot, Waldhorn, Soler97, Jruderman, Francvs, Classicalecon, Bruceschuman, Auntof6, Cheerios69, Excirial, Hans Adler, Hugo Herbelin, Johnuniq, Pgallert, Fluffernutter, AnomieBOT, Danielt998, Materialscientist, Ched, MetaNest, Kivgaen, Pinethicket, Minusia, Oxonienses, Gamewizard71, Trappist the monk, ItsZippy, Diannaa, Rbaleksandar, Jmencisom, Winner 42, Dcirovic, D.Lazard, Puffin, Tijfo098, SemanticMantis, LZ6387, ClueBot NG, LuluQ, Abecedarius, Delusion23, Jiri 1984, Calisthenis, Helpful Pixie Bot, Shantnup, BG19bot, Northamerica1000, Ivannoriel, Supernerd11, Robert Thyder, LanaEditArticles, Brad7777, Wolfmanx122, Proxyma, Sofia karampataki, Muammar Gaddafi, Cerabot~enwiki, Fuebar, Telfordbuck, Ruby Murray, Rlwood1, Shevek1981, Seppi333, The Rahul Jain, Matthew Kastor, LarsHugo, Happy Attack Dog, Abc 123 def 456, Trax support, Lich counter, Mathematical Truth, LukasMatt, Anjana Larka, Petr.savicky, Myra Gul, DiscantX, Striker0614, Masih.bist, KasparBot, Jamieddd, MegaManiaZ, Bawb131, Prayasjain7, Striker0615 and Anonymous: 120
- **Logic gate** *Source:* https://en.wikipedia.org/wiki/Logic_gate?oldid=709114124 *Contributors:* AxelBoldt, Magnus Manske, Peter Winnberg, Derek Ross, MarXidad, The Anome, BenBaker, Jkominek, Mudlock, Heron, Stevertigo, Frecklefoot, RTC, Michael Hardy, Booyabazooka, Mahjongg, Dominus, SGBailey, Ixfd64, Karada, Mac, Glenn, Netsnipe, GRAHAMUK, Arteitle, Reddi, Dysprosia, Colin Marquardt, Maximus Rex, Mrand, Furrykef, Omegatron, Jni, Sjorford, Robbot, Lord Kelvin, Pingveno, Bkell, Ianml, Paul Murray, Mushroom, Ancheta Wis, Centrx, Giftlite, Andy, DavidCary, Peruvianllama, Everyking, Pashute, AJim, Andris, Espetkov, Vadmium, LucasVB, Kaldari, CSTAR, Creidieki, Jlang, Kineox~enwiki, Mormegil, Discospinster, Rich Farmbrough, Luzian~enwiki, Roo72, LindsayH, SocratesJedi, ESkog, ZeroOne, Plugwash, Nabla, CanisRufus, Aecis, Diomidis Spinellis, Smalljim, La goutte de pluie, Hooperbloob, Jumbuck, Guy Harris, Arthena, Blues-harp, Lectonar, Pion, Bantman, N313t3~enwiki, BRW, Wtshymanski, Rick Sidwell, Cburnett, Deadworm222, Bonzo, Alai, Axeman89, LunaticFringe, Bookandcoffee, Dan100, Cipherswarm, Smark33021, Boothy443, Mindmatrix, Jonathan de Boyne Pollard, Bkkbrad, VanFowler, Kglavin, Karmosin, The Nameless, V8rik, BD2412, Syndicate, ZanderSchubert, GOD, Bruce1ee, Ademkader, DoubleBlue, Firebug, Mirror Vax, Latka, Ewlyahoocom, Swtpc6800, Fresheneesz, Vonkje, DVdm, Bgwhite, The Rambling Man, YurikBot, Adam1213, RussBot, Akamad, Stephenb, Yyy, Robchurch, FreelanceWizard, Zwobot, Rohanmittal, StuRat, Reyk, Urocyon, HereToHelp, Anclation~enwiki, Easter Monkey, SorryGuy, AMbroodEY, JDspeeder1, Adam outler, Crystallina, SmackBot, Eveningmist, Jcbarr, Frymaster, Canthusus, Folajimi, Andy M. Wang, Lindosland, JoeKearney, SynergyBlades, Oli Filth, MovGP0, Lightspeedchick, Jjbeard~enwiki, Audriusa, Ian Burnet~enwiki, Can't sleep, clown will eat me, Nick Levine, KevM, Atilme, Epachamo, Hgilbert, Jon Awbrey, Shadow148, SashatoBot, Lambiam, Kuru, MagnaMopus, Athernar, Igor Markov, Mgiganteus1, JHunterJ, Vanished user 8ij3r8jwefi, Robert Bond, Dicklyon, Mets501, Dacium, JYi, J Di, Aeons, Rangi42, Marysunshine, Eassin, Tawkerbot2, DonkeyKong64, Drinibot, Circuit dreamer, Skoch3, Arnavion, Gregbard, Rajiv Beharie, Mblumber, Abhignarigala, Mello newf, Dancter, Tawkerbot4, DumbBOT, Omicronpersei8, Lordhatrus, Thijs!bot, Epbr123, N5iln, Al Lemos, Marek69, DmitTrix, James086, Towopedia, Izyt, Eleuther, Stannered, AntiVandalBot, USPatent, MER-C, Wasell, Massimiliano Lincetto, Bongwarrior, VoABot II, JNW, Yandman, Rhdv, M 3bdelqader, Robin S, Rickterp, MartinBot, Rettetast, Glrx, J.delanoy, Jonpro, Feis-Kontrol, Zen-in, Jeepday, Eibx, Bigdumbdinosaur, FreddieRic, Hanacy, Sunderland06, Cometstyles, Tiggerjay, Tygrrr, DorganBot, Alex:D, Barber32, Idioma-bot, VolkovBot, Hersfold, AlnoktaBOT, Lear’s Fool, Philip Trueman, PNG crusade bot, TXiKiBoT, Oshwah, GLPeterson, Mamidanna, Murugango, Djkrajnik, Salvar, The Tetrast, Corvus cornix, Jackfork, Inductiveload, Dirkbb, Updatebjarni, STEDMUNDS07, Logan, Neparis, SieBot, Niv.sarig, I Like Cheeseburgers, ToePeu.bot, Gerakibot, Teh Naab, Flyer22 Reborn, Berserkerus, Evaluist, Oxymoron83, Steven Crossin, WimdeValk, ClueBot, The Thing That Should Not Be, Rilak, Iandiver, Boing! said Zebedee, CounterVandalismBot, Namazu-tron, Alexbot, Ftbhrygvn, EddyJ07, Dspark76, Hans Adler, The Red, Abhishek Jacob, Horselover Frost, Versus22, Egmontaz, DumZiBoT, XLinkBot, Skarebo, Marylee23, MystBot, Iranway, Addbot, Willking1979, Melab-1, A0602336, Chef Super-Hot, Ashton1983, Vishnava, Fluffernutter, Rchard2scout, Hmorris94, Tyw7, Tide rolls, Lightbot, OlEnglish, Legobot, PlankBot, Luckas-bot, Ptbotgourou, THEN WHO WAS PHONE?, Knownot, Alienskull, AnomieBOT, 0x38I9J*, Jim1138, JackieBot, Piano non troppo, Keithbob, Materialscientist, Spirit469, Citation bot, Bean49, Xqbot, RMSfromFtC, Sketchmoose, Big angry doggy, Capricorn42, Coretheapple, RibotBOT, Elep2009, XPEHOPE3, Joaquin008, Vdsharma12, FrescoBot, Roman12345, Machine Elf 1735, Cannolis, Pinethicket, Jschnur, RedBot, MastiBot, Serols, SpaceFlight89, Forward Unto Dawn, Cnwilliams, Wikitikitaka, Blackenblue, Vrenator, Zvn, Clarkcj12, MrX, Meistro god, Galloping Moses, EmausBot, John of Reading, Trinibones, Wikipelli, Draconicfire, GOVIND SANGLI, Wayne Slam, Dmitry123456, Ontyx, Carmichael, Tijfo098, GrayFullbuster, Protoborg, Stevenglowa, ClueBot NG, Jack Greenmaven, Morgankevinj huggle, VladikVP, Marechal Ney, Masssly, Widr, Vibhijain, Jk2q3jrklse, Helpful Pixie Bot, Wbm1058, Lowercase sigmabot, Mark Arsten, CitationCleanerBot, Snow Blizzard, Husigeza, RscprinterBot, Safeskiboydunknoe, FrederickE, Teammm, Mrt3366, Rsmary, Sha-256, Harsh 2580, Lugia2453, Frosty, Itsmeshiva, Red-eyed demon, Jamesmcmahon0, Tentinator, SelfishSeahorse, Lilbonanza, Mz bankie, Jianhui67, Abhinav dw6, Cdouglas32, Trax support, TerryAlex, Gfdsfgfgfg, Areyoureadylouie, Anjana Larka, Charliegirl321, J92453, Bobbbbbbbbvvvvvcvcv, KasparBot, CLC-

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