**Electronics** is the branch of [science](http://en.wikipedia.org/wiki/Science), [engineering](http://en.wikipedia.org/wiki/Engineering) and [technology](http://en.wikipedia.org/wiki/Technology) that deals with [electrical circuits](http://en.wikipedia.org/wiki/Electrical_circuit) involving [active electrical components](http://en.wikipedia.org/wiki/Active_component)such as [vacuum tubes](http://en.wikipedia.org/wiki/Vacuum_tube), [transistors](http://en.wikipedia.org/wiki/Transistor), [diodes](http://en.wikipedia.org/wiki/Diode) and [integrated circuits](http://en.wikipedia.org/wiki/Integrated_circuit), and associated passive interconnection technologies. The [nonlinear](http://en.wikipedia.org/wiki/Nonlinear)behaviour of active components and their ability to control electron flows makes amplification of weak signals possible and is usually applied to [information](http://en.wikipedia.org/wiki/Information_processing) and [signal processing](http://en.wikipedia.org/wiki/Signal_processing). Similarly, the ability of electronic devices to act as switches makes digital information processing possible. Interconnection technologies such as [circuit boards](http://en.wikipedia.org/wiki/Circuit_board), electronics packaging technology, and other varied forms of communication infrastructure complete circuit functionality and transform the mixed components into a working [system](http://en.wikipedia.org/wiki/System).

Electronics is distinct from [electrical](http://en.wikipedia.org/wiki/Electricity) and [electro-mechanical](http://en.wikipedia.org/wiki/Electro-mechanical) science and technology, which deals with the generation, distribution, switching, storage and conversion of electrical energy to and from other energy forms using [wires](http://en.wikipedia.org/wiki/Wire), [motors](http://en.wikipedia.org/wiki/Motor), [generators](http://en.wikipedia.org/wiki/Generator), [batteries](http://en.wikipedia.org/wiki/Battery_(electricity)),[switches](http://en.wikipedia.org/wiki/Switch), [relays](http://en.wikipedia.org/wiki/Relay), [transformers](http://en.wikipedia.org/wiki/Transformer), [resistors](http://en.wikipedia.org/wiki/Resistor) and other [passive components](http://en.wikipedia.org/wiki/Passive_component). This distinction started around 1906 with the invention by [Lee De Forest](http://en.wikipedia.org/wiki/Lee_De_Forest) of the [triode](http://en.wikipedia.org/wiki/Triode), which made electrical [amplification](http://en.wikipedia.org/wiki/Amplifier) 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](http://en.wikipedia.org/wiki/Transmitter),[receivers](http://en.wikipedia.org/wiki/Receiver_(radio)) and [vacuum tubes](http://en.wikipedia.org/wiki/Vacuum_tube).

Today, most electronic devices use [semiconductor](http://en.wikipedia.org/wiki/Semiconductor) components to perform electron control. The study of semiconductor devices and related technology is considered a branch of [solid state physics](http://en.wikipedia.org/wiki/Solid_state_physics), whereas the design and construction of [electronic circuits](http://en.wikipedia.org/wiki/Electronic_circuit) to solve practical problems come under [electronics engineering](http://en.wikipedia.org/wiki/Electronics_engineering). This article focuses on [engineering](http://en.wikipedia.org/wiki/Engineering) aspects of electronics.

[**Electronic devices and components**](http://en.wikipedia.org/wiki/Electronics#Electronic_devices_and_components)

An electronic component is any physical entity in an electronic system used to affect the electrons or their associated fields in a desired 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](http://en.wikipedia.org/wiki/Printed_circuit_board) (PCB), to create an electronic circuit with a particular function (for example an [amplifier](http://en.wikipedia.org/wiki/Amplifier), [radio receiver](http://en.wikipedia.org/wiki/Radio_receiver), or [oscillator](http://en.wikipedia.org/wiki/Electronic_oscillator)). Components may be packaged singly or in more complex groups as [integrated circuits](http://en.wikipedia.org/wiki/Integrated_circuits). Some common electronic components are [capacitors](http://en.wikipedia.org/wiki/Capacitor), [inductors](http://en.wikipedia.org/wiki/Inductor), [resistors](http://en.wikipedia.org/wiki/Resistor), [diodes](http://en.wikipedia.org/wiki/Diode), [transistors](http://en.wikipedia.org/wiki/Transistor), etc. Components are often categorized as active (e.g. transistors and [thyristors](http://en.wikipedia.org/wiki/Thyristor)) or [passive](http://en.wikipedia.org/wiki/Passivity_(engineering)) (e.g. resistors and capacitors).

[**Early electronic components**](http://en.wikipedia.org/wiki/Electronics#Early_electronic_components)

[Vacuum tubes](http://en.wikipedia.org/wiki/Vacuum_tube) were one of the earliest electronic components. They dominated electronics until the 1950s. Since that time, solid state devices have all but completely taken over. Vaccum tubes are still used in some specialist applications such as [high power RF amplifiers](http://en.wikipedia.org/wiki/Valve_RF_amplifier), [cathode ray tubes](http://en.wikipedia.org/wiki/Cathode_ray_tube), and some [microwave devices](http://en.wikipedia.org/wiki/Cavity_magnetron).

[**Types of circuits**](http://en.wikipedia.org/wiki/Electronics#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

### [*Analogue signals*](http://en.wikipedia.org/wiki/Analog_electronics#Analogue_signals)

An analogue signal uses some attribute of the medium to convey the signal's information. For example, an [aneroid barometer](http://en.wikipedia.org/wiki/Barometer#Aneroid_barometers) uses the [angular position](http://en.wikipedia.org/wiki/Angular_position) of a needle as the signal to convey the information of changes in [atmospheric pressure](http://en.wikipedia.org/wiki/Atmospheric_pressure).[[2]](http://en.wikipedia.org/wiki/Analog_electronics#cite_note-1) Electrical signals may represent information by changing their voltage, current, frequency, or total charge. Information is converted from some other physical form (such as sound, light, temperature, pressure, position) to an electrical signal by a [transducer](http://en.wikipedia.org/wiki/Transducer) which converts one type of energy into another (e.g. a [microphone](http://en.wikipedia.org/wiki/Microphone)).[[3]](http://en.wikipedia.org/wiki/Analog_electronics#cite_note-2)

The signals take any value from a given range, and each unique signal value represents different information. Any change in the signal is meaningful, and each level of the signal represents a different level of the phenomenon that it represents. For example, suppose the signal is being used to represent temperature, with one [volt](http://en.wikipedia.org/wiki/Volt) representing one degree Celsius. In such a system 10 volts would represent 10 degrees, and 10.1 volts would represent 10.1 degrees.

Another method of conveying an analogue signal is to use [modulation](http://en.wikipedia.org/wiki/Modulation). In this, some base carrier signal has one of its properties altered: [amplitude modulation](http://en.wikipedia.org/wiki/Amplitude_modulation) (AM) involves altering the amplitude of a sinusoidal voltage waveform by the source information, [frequency modulation](http://en.wikipedia.org/wiki/Frequency_modulation) (FM) changes the frequency. Other techniques, such as [phase modulation](http://en.wikipedia.org/wiki/Phase_modulation) or changing the phase of the carrier signal, are also used.[[4]](http://en.wikipedia.org/wiki/Analog_electronics#cite_note-3)

In an analogue sound recording, the variation in pressure of a sound striking a [microphone](http://en.wikipedia.org/wiki/Microphone) creates a corresponding variation in the current passing through it or voltage across it. An increase in the volume of the sound causes the fluctuation of the current or voltage to increase proportionally while keeping the same [waveform](http://en.wikipedia.org/wiki/Waveform) or shape.

[Mechanical](http://en.wikipedia.org/wiki/Mechanics), [pneumatic](http://en.wikipedia.org/wiki/Pneumatic), [hydraulic](http://en.wikipedia.org/wiki/Hydraulic) and other systems may also use analogue signals.

[Inherent noise](http://en.wikipedia.org/wiki/Analog_electronics#Inherent_noise)

Analogue systems invariably include [noise](http://en.wikipedia.org/wiki/Noise_(electronics)); that is, random disturbances or variations, some caused by the random thermal vibrations of atomic particles. Since all variations of an analogue signal are significant, any disturbance is equivalent to a change in the original signal and so appears as noise.[[5]](http://en.wikipedia.org/wiki/Analog_electronics#cite_note-4) As the signal is copied and re-copied, or transmitted over long distances, these random variations become more significant and lead to signal degradation. Other sources of noise may include external electrical signals or poorly designed components. These disturbances are reduced by [shielding](http://en.wikipedia.org/wiki/Shielding), and using [low-noise amplifiers](http://en.wikipedia.org/wiki/Low-noise_amplifier) (LNA).

[Analogue vs. digital electronics](http://en.wikipedia.org/wiki/Analog_electronics#Analogue_vs._digital_electronics)

Since the information is encoded differently in analogue and [digital electronics](http://en.wikipedia.org/wiki/Digital_electronics), the way they process a signal is consequently different. All operations that can be performed on an analogue signal such as [amplification](http://en.wikipedia.org/wiki/Amplifier), [filtering](http://en.wikipedia.org/wiki/Electronic_filter), limiting, and others, can also be duplicated in the digital domain. Every digital circuit is also an analogue circuit, in that the behaviour of any digital circuit can be explained using the rules of analogue circuits.

The first electronic devices invented and [mass produced](http://en.wikipedia.org/wiki/Mass_production) were analogue. The use of [microelectronics](http://en.wikipedia.org/wiki/Microelectronics) has reduced the cost of digital techniques and now makes digital methods feasible and cost-effective such as in the field of[human-machine communication by voice](http://en.wikipedia.org/wiki/Human-computer_interaction#Future_developments).[[7]](http://en.wikipedia.org/wiki/Analog_electronics#cite_note-6)

The main differences between analogue and digital electronics are listed below:

### *Noise*

Because of the way information is encoded in analogue circuits, they are much more susceptible to [noise](http://en.wikipedia.org/wiki/Noise) than digital circuits, since a small change in the signal can represent a significant change in the information present in the signal and can cause the information present to be lost. Since digital signals take on one of only two different values, a disturbance would have to be about one-half the magnitude of the digital signal to cause an error; this property of digital circuits can be exploited to make [signal processing](http://en.wikipedia.org/wiki/Digital_signal_processing) noise-resistant. In digital electronics, because the information is [quantized](http://en.wikipedia.org/wiki/Quantization_(signal_processing)), as long as the signal stays inside a range of values, it represents the same information. Digital circuits use this principle to regenerate the signal at each [logic gate](http://en.wikipedia.org/wiki/Logic_gate), lessening or removing noise.[[8]](http://en.wikipedia.org/wiki/Analog_electronics#cite_note-7)

### *Precision*

A number of factors affect how precise a signal is, mainly the noise present in the original signal and the noise added by processing. See [signal-to-noise ratio](http://en.wikipedia.org/wiki/Signal-to-noise_ratio). Fundamental physical limits such as the [shot noise](http://en.wikipedia.org/wiki/Shot_noise) in components limits the resolution of analogue signals. In digital electronics additional precision is obtained by using additional digits to represent the signal; the practical limit in the number of digits is determined by the performance of the[analogue-to-digital converter](http://en.wikipedia.org/wiki/Analogue-to-digital_converter) (ADC), since digital operations can usually be performed without loss of precision. The ADC takes an analogue signal and changes into a series of [binary numbers](http://en.wikipedia.org/wiki/Binary_number). The ADC may be used in simple digital display devices e. g. thermometers, light meters but it may also be used in digital sound recording and in data acquisition. However, a [digital-to-analogue converter](http://en.wikipedia.org/wiki/Digital-to-analogue_converter) (DAC) is used to change a digital signal to an analogue signal. A DAC takes a series of binary numbers and converts it to an analogue signal. It is common to find a DAC in the gain-control system of an [op-amp](http://en.wikipedia.org/wiki/Op-amp) which in turn may be used to control digital amplifiers and filters.[[9]](http://en.wikipedia.org/wiki/Analog_electronics#cite_note-8)

### *Design difficulty*

Analogue circuits are harder to design, requiring more skill, than comparable digital systems.[[*citation needed*](http://en.wikipedia.org/wiki/Wikipedia:Citation_needed)] This is one of the main reasons why digital systems have become more common than analogue devices. An analogue circuit must be designed by hand, and the process is much less automated than for digital systems. However, if a digital electronic device is to interact with the real world, it will always need an analogue interface.[[10]](http://en.wikipedia.org/wiki/Analog_electronics#cite_note-9) For example, every [digital radio](http://en.wikipedia.org/wiki/Digital_radio) receiver has an analogue preamplifier as the first stage in the receive chain.

### Digital circuits

**Digital electronics** represent [signals](http://en.wikipedia.org/wiki/Signal_(electronics)) by discrete bands of [analog](http://en.wikipedia.org/wiki/Analog_electronics) [levels](http://en.wikipedia.org/wiki/Electrical_potential), rather than by a continuous range. All levels within a band represent the same signal state. Relatively small changes to the analog signal levels due to[manufacturing tolerance](http://en.wikipedia.org/wiki/Engineering_tolerance), [signal attenuation](http://en.wikipedia.org/wiki/Path_loss) or [parasitic noise](http://en.wikipedia.org/wiki/Noise_(electronics)) do not leave the discrete envelope, and as a result are ignored by signal state sensing circuitry.

In most cases the number of these states is two, and they are represented by two voltage bands: one near a reference value (typically termed as "ground" or zero volts) and a value near the supply voltage, corresponding to the "false" ("0") and "true" ("1") values of the [Boolean domain](http://en.wikipedia.org/wiki/Boolean_domain) respectively.

Digital techniques are useful because it is easier to get an electronic device to switch into one of a number of known states than to accurately reproduce a continuous range of values.

Digital electronic circuits are usually made from large assemblies of [logic gates](http://en.wikipedia.org/wiki/Logic_gate), simple electronic representations of [Boolean logic functions](http://en.wikipedia.org/wiki/Boolean_logic#Digital_electronic_circuit_design).

[**Advantages**](http://en.wikipedia.org/wiki/Digital_electronics#Advantages)

One advantage of digital circuits when compared to analog circuits is [[2]](http://en.wikipedia.org/wiki/Digital_electronics#cite_note-1) signals represented digitally can be transmitted without degradation due to [noise](http://en.wikipedia.org/wiki/Noise). For example, a continuous audio signal, transmitted as a sequence of 1s and 0s, can be reconstructed without error provided the noise picked up in transmission is not enough to prevent identification of the 1s and 0s. An hour of music can be stored on a [compact disc](http://en.wikipedia.org/wiki/Compact_disc) using about 6 billion binary digits.

In a digital system, a more precise representation of a signal can be obtained by using more binary digits to represent it. While this requires more digital circuits to process the signals, each digit is handled by the same kind of hardware. In an analog system, additional resolution requires fundamental improvements in the linearity and noise characteristics of each step of the [signal chain](http://en.wikipedia.org/wiki/Signal_chain_(signal_processing_chain)).

Computer-controlled digital systems can be controlled by software, allowing new functions to be added without changing hardware. Often this can be done outside of the factory by updating the product's software. So, the product's design errors can be corrected after the product is in a customer's hands.

Information storage can be easier in digital systems than in analog ones. The noise-immunity of digital systems permits data to be stored and retrieved without degradation. In an analog system, noise from aging and wear degrade the information stored. In a digital system, as long as the total noise is below a certain level, the information can be recovered perfectly.

[**Disadvantages**](http://en.wikipedia.org/wiki/Digital_electronics#Disadvantages)

In some cases, digital circuits use more energy than analog circuits to accomplish the same tasks, thus producing more heat which increases the complexity of the circuits such as the inclusion of heat sinks. In portable or battery-powered systems this can limit use of digital systems.

For example, battery-powered cellular telephones often use a low-power analog front-end to [amplify](http://en.wikipedia.org/wiki/Amplifier) and [tune](http://en.wikipedia.org/wiki/Tuner_(electronics)) in the [radio](http://en.wikipedia.org/wiki/Radio) signals from the base station. However, a base station has grid power and can use power-hungry, but very flexible [software radios](http://en.wikipedia.org/wiki/Software_radio). Such base stations can be easily reprogrammed to process the signals used in new cellular standards.

Digital circuits are sometimes more expensive, especially in small quantities.

Most useful digital systems must translate from continuous analog signals to discrete digital signals. This causes [quantization errors](http://en.wikipedia.org/wiki/Quantization_error). Quantization error can be reduced if the system stores enough digital data to represent the signal to the desired degree of [fidelity](http://en.wikipedia.org/wiki/Fidelity). The [Nyquist-Shannon sampling theorem](http://en.wikipedia.org/wiki/Nyquist-Shannon_sampling_theorem) provides an important guideline as to how much digital data is needed to accurately portray a given analog signal.

In some systems, if a single piece of digital data is lost or misinterpreted, the meaning of large blocks of related data can completely change. Because of the [cliff effect](http://en.wikipedia.org/wiki/Cliff_effect), it can be difficult for users to tell if a particular system is right on the edge of failure, or if it can tolerate much more noise before failing.

Digital fragility can be reduced by designing a digital system for robustness. For example, a [parity bit](http://en.wikipedia.org/wiki/Parity_bit) or other [error management method](http://en.wikipedia.org/wiki/Error_correction_and_detection) can be inserted into the signal path. These schemes help the system detect errors, and then either [correct the errors](http://en.wikipedia.org/wiki/Error_detection_and_correction), or at least ask for a new copy of the data. In a state-machine, the state transition logic can be designed to catch unused states and trigger a reset sequence or other error recovery routine.

Digital memory and transmission systems can use techniques such as error detection and correction to use additional data to correct any errors in transmission and storage.

On the other hand, some techniques used in digital systems make those systems more vulnerable to single-bit errors. These techniques are acceptable when the underlying bits are reliable enough that such errors are highly unlikely. A single-bit error in audio data stored directly as [linear pulse code modulation](http://en.wikipedia.org/wiki/Linear_pulse_code_modulation) (such as on a [CD-ROM](http://en.wikipedia.org/wiki/CD-ROM)) causes, at worst, a single click. Instead, many people use [audio compression](http://en.wikipedia.org/wiki/Audio_compression_(data)) to save storage space and download time, even though a single-bit error may corrupt the entire song.

[**Analog issues in digital circuits**](http://en.wikipedia.org/wiki/Digital_electronics#Analog_issues_in_digital_circuits)

Digital circuits are made from analog components. The design must assure that the analog nature of the components doesn't dominate the desired digital behavior. Digital systems must manage noise and timing margins, parasitic inductances and capacitances, and [filter](http://en.wikipedia.org/wiki/Electronic_filter) power connections.

Bad designs have intermittent problems such as "glitches", vanishingly-fast pulses that may trigger some logic but not others, "[runt pulses](http://en.wikipedia.org/wiki/Runt_pulse)" that do not reach valid "threshold" voltages, or unexpected ("undecoded") combinations of logic states.

Additionally, where clocked digital systems interface to analogue systems or systems that are driven from a different clock, the digital system can be subject to [metastability](http://en.wikipedia.org/wiki/Metastability_in_electronics) where a change to the input violates the set-up time for a digital input latch. This situation will self-resolve, but will take a random time, and while it persists can result in invalid signals being propagated within the digital system for a short time.

Since digital circuits are made from analog components, digital circuits calculate more slowly than low-precision analog circuits that use a similar amount of space and power. However, the digital circuit will calculate more repeatably, because of its high noise immunity. On the other hand, in the high-precision domain (for example, where 14 or more bits of precision are needed), analog circuits require much more power and area than digital equivalents.

[**Construction**](http://en.wikipedia.org/wiki/Digital_electronics#Construction)

A digital circuit is often constructed from small electronic circuits called [logic gates](http://en.wikipedia.org/wiki/Logic_gate) that can be used to create [combinational logic](http://en.wikipedia.org/wiki/Combinational_logic). Each logic gate represents a function of [boolean logic](http://en.wikipedia.org/wiki/Boolean_logic). A logic gate is an arrangement of electrically controlled switches, better known as [transistors](http://en.wikipedia.org/wiki/Transistors).

Each logic symbol is represented by a different shape. The actual set of shapes was introduced in 1984 under IEEE\ANSI standard 91-1984. "The logic symbol given under this standard are being increasingly used now and have even started appearing in the literature published by manufacturers of digital integrated circuits."[[3]](http://en.wikipedia.org/wiki/Digital_electronics#cite_note-2)

The output of a logic gate is an electrical [flow](http://en.wikipedia.org/wiki/Electrical_current) or voltage, that can, in turn, control more logic gates.

Logic gates often use the fewest number of transistors in order to reduce their size, power consumption and cost, and increase their reliability.

[Integrated circuits](http://en.wikipedia.org/wiki/Integrated_circuit) are the least expensive way to make logic gates in large volumes. Integrated circuits are usually designed by engineers using [electronic design automation](http://en.wikipedia.org/wiki/Electronic_design_automation) software (see below for more information).

Another form of digital circuit is constructed from lookup tables, (many sold as "[programmable logic devices](http://en.wikipedia.org/wiki/Programmable_logic_device)", though other kinds of PLDs exist). Lookup tables can perform the same functions as machines based on logic gates, but can be easily reprogrammed without changing the wiring. This means that a designer can often repair design errors without changing the arrangement of wires. Therefore, in small volume products, programmable logic devices are often the preferred solution. They are usually designed by engineers using electronic design automation software.

When the volumes are medium to large, and the logic can be slow, or involves complex algorithms or sequences, often a small [microcontroller](http://en.wikipedia.org/wiki/Microcontroller) is [programmed](http://en.wikipedia.org/wiki/Computer_program) to make an [embedded system](http://en.wikipedia.org/wiki/Embedded_system). These are usually programmed by[software engineers](http://en.wikipedia.org/wiki/Software_engineering).

When only one digital circuit is needed, and its design is totally customized, as for a factory production line controller, the conventional solution is a [programmable logic controller](http://en.wikipedia.org/wiki/Programmable_logic_controller), or PLC. These are usually programmed by electricians, using [ladder logic](http://en.wikipedia.org/wiki/Ladder_logic).

### Structure of digital systems

Engineers use many methods to minimize logic functions, in order to reduce the circuit's complexity. When the complexity is less, the circuit also has fewer errors and less electronics, and is therefore less expensive.

The most widely used simplification is a minimization algorithm like the [Espresso heuristic logic minimizer](http://en.wikipedia.org/wiki/Espresso_heuristic_logic_minimizer) within a [CAD](http://en.wikipedia.org/wiki/Computer-aided_design) system, although historically, [binary decision diagrams](http://en.wikipedia.org/wiki/Binary_decision_diagrams), an automated [Quine–McCluskey algorithm](http://en.wikipedia.org/wiki/Quine%E2%80%93McCluskey_algorithm), [truth tables](http://en.wikipedia.org/wiki/Truth_table),[Karnaugh Maps](http://en.wikipedia.org/wiki/Karnaugh_Map), and [Boolean algebra](http://en.wikipedia.org/wiki/Boolean_algebra_(logic)) have been used.

Representations are crucial to an engineer's design of digital circuits. Some analysis methods only work with particular representations.

The classical way to represent a digital circuit is with an equivalent set of [logic gates](http://en.wikipedia.org/wiki/Logic_gates). Another way, often with the least electronics, is to construct an equivalent system of electronic switches (usually [transistors](http://en.wikipedia.org/wiki/Transistor)). One of the easiest ways is to simply have a memory containing a truth table. The inputs are fed into the address of the memory, and the data outputs of the memory become the outputs.

For automated analysis, these representations have digital file formats that can be processed by computer programs. Most digital engineers are very careful to select computer programs ("tools") with compatible file formats.

To choose representations, engineers consider types of digital systems. Most digital systems divide into "combinational systems" and "sequential systems." A combinational system always presents the same output when given the same inputs. It is basically a representation of a set of logic functions, as already discussed.

A sequential system is a combinational system with some of the outputs fed back as inputs. This makes the digital machine perform a "sequence" of operations. The simplest sequential system is probably a [flip flop](http://en.wikipedia.org/wiki/Flip-flop_(electronics)), a mechanism that represents a [binary](http://en.wikipedia.org/wiki/Binary_number_system) [digit](http://en.wikipedia.org/wiki/Numerical_digit) or "[bit](http://en.wikipedia.org/wiki/Bit)".

Sequential systems are often designed as [state machines](http://en.wikipedia.org/wiki/State_machine). In this way, engineers can design a system's gross behavior, and even test it in a simulation, without considering all the details of the logic functions.

Sequential systems divide into two further subcategories. ["Synchronous" sequential systems](http://en.wikipedia.org/wiki/Synchronous_system) change state all at once, when a "clock" signal changes state. ["Asynchronous" sequential systems](http://en.wikipedia.org/wiki/Asynchronous_system) propagate changes whenever inputs change. Synchronous sequential systems are made of well-characterized asynchronous circuits such as flip-flops, that change only when the clock changes, and which have carefully designed timing margins.

The usual way to implement a synchronous sequential state machine is to divide it into a piece of combinational logic and a set of flip flops called a "state register." Each time a clock signal ticks, the state register captures the feedback generated from the previous state of the combinational logic, and feeds it back as an unchanging input to the combinational part of the state machine. The fastest rate of the clock is set by the most time-consuming logic calculation in the combinational logic.

The state register is just a representation of a binary number. If the states in the state machine are numbered (easy to arrange), the logic function is some combinational logic that produces the number of the next state.

In comparison, asynchronous systems are very hard to design because all possible states, in all possible timings must be considered. The usual method is to construct a table of the minimum and maximum time that each such state can exist, and then adjust the circuit to minimize the number of such states, and force the circuit to periodically wait for all of its parts to enter a compatible state (this is called "self-resynchronization"). Without such careful design, it is easy to accidentally produce asynchronous logic that is "unstable", that is, real electronics will have unpredictable results because of the cumulative delays caused by small variations in the values of the electronic components. Certain circuits (such as the synchronizer flip-flops, switch [debouncers](http://en.wikipedia.org/wiki/Debounce), [arbiters](http://en.wikipedia.org/wiki/Arbiter_(electronics)), and the like which allow external unsynchronized signals to enter synchronous logic circuits) are inherently asynchronous in their design and must be analyzed as such.

As of 2005, almost all digital machines are synchronous designs because it is much easier to create and verify a synchronous design—the software currently used to simulate digital machines does not yet handle asynchronous designs. However, asynchronous logic is thought to be superior, if it can be made to work, because its speed is not constrained by an arbitrary clock; instead, it runs at the maximum speed of its logic gates. Building an asynchronous circuit using faster parts makes the circuit faster.

Many digital systems are data flow machines. These are usually designed using synchronous [register transfer logic](http://en.wikipedia.org/wiki/Register_transfer_level), using hardware description languages such as [VHDL](http://en.wikipedia.org/wiki/VHDL) or [Verilog](http://en.wikipedia.org/wiki/Verilog).

In register transfer logic, binary [numbers](http://en.wikipedia.org/wiki/Number) are stored in groups of flip flops called [registers](http://en.wikipedia.org/wiki/Processor_register). The outputs of each register are a bundle of wires called a "[bus](http://en.wikipedia.org/wiki/Computer_bus)" that carries that number to other calculations. A calculation is simply a piece of combinational logic. Each calculation also has an output bus, and these may be connected to the inputs of several registers. Sometimes a register will have a [multiplexer](http://en.wikipedia.org/wiki/Multiplexer) on its input, so that it can store a number from any one of several buses. Alternatively, the outputs of several items may be connected to a bus through [buffers](http://en.wikipedia.org/wiki/3-state) that can turn off the output of all of the devices except one. A sequential state machine controls when each register accepts new data from its input.

In the 1980s, some researchers discovered that almost all synchronous register-transfer machines could be converted to asynchronous designs by using first-in-first-out synchronization logic. In this scheme, the digital machine is characterized as a set of data flows. In each step of the flow, an asynchronous "synchronization circuit" determines when the outputs of that step are valid, and presents a signal that says, "grab the data" to the stages that use that stage's inputs. It turns out that just a few relatively simple synchronization circuits are needed.

The most general-purpose register-transfer logic machine is a [computer](http://en.wikipedia.org/wiki/Computer). This is basically an [automatic](http://en.wikipedia.org/wiki/Automaton) binary [abacus](http://en.wikipedia.org/wiki/Abacus). The [control unit](http://en.wikipedia.org/wiki/Control_unit) of a computer is usually designed as a [microprogram](http://en.wikipedia.org/wiki/Microprogram) run by a [microsequencer](http://en.wikipedia.org/wiki/Microsequencer). A microprogram is much like a player-piano roll. Each table entry or "word" of the microprogram commands the state of every bit that controls the computer. The sequencer then counts, and the count addresses the memory or combinational logic machine that contains the microprogram. The bits from the microprogram control the [arithmetic logic unit](http://en.wikipedia.org/wiki/Arithmetic_logic_unit), [memory](http://en.wikipedia.org/wiki/Memory) and other parts of the computer, including the microsequencer itself.

In this way, the complex task of designing the controls of a computer is reduced to a simpler task of programming a collection of much simpler logic machines.

[Computer architecture](http://en.wikipedia.org/wiki/Computer_architecture) is a specialized engineering activity that tries to arrange the registers, calculation logic, buses and other parts of the computer in the best way for some purpose. Computer architects have applied large amounts of ingenuity to computer design to reduce the cost and increase the speed and immunity to programming errors of computers. An increasingly common goal is to reduce the power used in a battery-powered computer system, such as a cell-phone. Many computer architects serve an extended apprenticeship as microprogrammers.

"Specialized computers" are usually a conventional computer with a special-purpose microprogram.

### Automated design tools

To save costly engineering effort, much of the effort of designing large logic machines has been automated. The computer programs are called "[electronic design automation](http://en.wikipedia.org/wiki/Electronic_design_automation) tools" or just "EDA."

Simple truth table-style descriptions of logic are often optimized with EDA that automatically produces reduced systems of logic gates or smaller lookup tables that still produce the desired outputs. The most common example of this kind of software is the [Espresso heuristic logic minimizer](http://en.wikipedia.org/wiki/Minilog).

Most practical algorithms for optimizing large logic systems use [algebraic manipulations](http://en.wikipedia.org/wiki/Quine%E2%80%93McCluskey_algorithm) or [binary decision diagrams](http://en.wikipedia.org/wiki/Binary_decision_diagram), and there are promising experiments with [genetic algorithms](http://en.wikipedia.org/wiki/Genetic_algorithm) and [annealing optimizations](http://en.wikipedia.org/wiki/Simulated_annealing).

To automate costly engineering processes, some EDA can take [state tables](http://en.wikipedia.org/wiki/State_table) that describe [state machines](http://en.wikipedia.org/wiki/State_machine) and automatically produce a truth table or a [function table](http://en.wikipedia.org/w/index.php?title=Function_table&action=edit&redlink=1) for the [combinational logic](http://en.wikipedia.org/wiki/Combinational_logic) of a state machine. The state table is a piece of text that lists each state, together with the conditions controlling the transitions between them and the belonging output signals.

It is common for the function tables of such computer-generated state-machines to be optimized with logic-minimization software such as [Minilog](http://en.wikipedia.org/wiki/Minilog).

Often, real logic systems are designed as a series of sub-projects, which are combined using a "tool flow." The tool flow is usually a "script," a simplified computer language that can invoke the software design tools in the right order.

Tool flows for large logic systems such as [microprocessors](http://en.wikipedia.org/wiki/Microprocessor) can be thousands of commands long, and combine the work of hundreds of engineers.

Writing and debugging tool flows is an established engineering specialty in companies that produce digital designs. The tool flow usually terminates in a detailed computer file or set of files that describe how to physically construct the logic. Often it consists of instructions to draw the [transistors](http://en.wikipedia.org/wiki/Transistors) and wires on an integrated circuit or a [printed circuit board](http://en.wikipedia.org/wiki/Printed_circuit_board).

Parts of tool flows are "debugged" by verifying the outputs of simulated logic against expected inputs. The test tools take computer files with sets of inputs and outputs, and highlight discrepancies between the simulated behavior and the expected behavior.

Once the input data is believed correct, the design itself must still be verified for correctness. Some tool flows verify designs by first producing a design, and then scanning the design to produce compatible input data for the tool flow. If the scanned data matches the input data, then the tool flow has probably not introduced errors.

The functional verification data are usually called "test vectors." The functional test vectors may be preserved and used in the factory to test that newly constructed logic works correctly. However, functional test patterns don't discover common fabrication faults. Production tests are often designed by software tools called "[test pattern generators](http://en.wikipedia.org/wiki/Automatic_test_pattern_generation)". These generate test vectors by examining the structure of the logic and systematically generating tests for particular faults. This way the [fault coverage](http://en.wikipedia.org/wiki/Fault_coverage) can closely approach 100%, provided the design is properly made testable (see next section).

Once a design exists, and is verified and testable, it often needs to be processed to be manufacturable as well. Modern integrated circuits have features smaller than the wavelength of the light used to expose the photoresist. Manufacturability software adds interference patterns to the exposure masks to eliminate open-circuits, and enhance the masks' contrast.

### Design for testability

"There are several reasons for testing a logic circuit. When the circuit is first developed, it is necessary to verify that the design circuit meets the required functional and timing specifications. When multiple copies of a correctly designed circuit are being manufactured, it is essential to test each copy to ensure that the manufacturing process has not introduced any flaws.[[4]](http://en.wikipedia.org/wiki/Digital_electronics#cite_note-3)

A large logic machine (say, with more than a hundred logical variables) can have an astronomical number of possible states. Obviously, in the factory, testing every state is impractical if testing each state takes a microsecond, and there are more states than the number of microseconds since the universe began. Unfortunately, this ridiculous-sounding case is typical.

Fortunately, large logic machines are almost always designed as assemblies of smaller logic machines. To save time, the smaller sub-machines are isolated by permanently-installed "design for test" circuitry, and are tested independently.

One common test scheme known as "scan design" moves test bits serially (one after another) from external test equipment through one or more serial [shift registers](http://en.wikipedia.org/wiki/Shift_register) known as "scan chains". Serial scans have only one or two wires to carry the data, and minimize the physical size and expense of the infrequently-used test logic.

After all the test data bits are in place, the design is reconfigured to be in "normal mode" and one or more clock pulses are applied, to test for faults (e.g. stuck-at low or stuck-at high) and capture the test result into flip-flops and/or latches in the scan shift register(s). Finally, the result of the test is shifted out to the block boundary and compared against the predicted "good machine" result.

In a board-test environment, serial to parallel testing has been formalized with a standard called "[JTAG](http://en.wikipedia.org/wiki/JTAG)" (named after the "Joint Test Action Group" that proposed it).

Another common testing scheme provides a test mode that forces some part of the logic machine to enter a "test cycle." The test cycle usually exercises large independent parts of the machine.

### Trade-offs

Several numbers determine the practicality of a system of digital logic. Engineers explored numerous electronic devices to get an ideal combination of [fanout](http://en.wikipedia.org/wiki/Fanout), speed, low cost and reliability.

The cost of a logic gate is crucial. In the 1930s, the earliest digital logic systems were constructed from telephone relays because these were inexpensive and relatively reliable. After that, engineers always used the cheapest available electronic switches that could still fulfill the requirements.

The earliest integrated circuits were a happy accident. They were constructed not to save money, but to save weight, and permit the [Apollo Guidance Computer](http://en.wikipedia.org/wiki/Apollo_Guidance_Computer) to control an [inertial guidance system](http://en.wikipedia.org/wiki/Inertial_guidance_system) for a spacecraft. The first integrated circuit logic gates cost nearly $50 (in 1960 dollars, when an engineer earned $10,000/year). To everyone's surprise, by the time the circuits were mass-produced, they had become the least-expensive method of constructing digital logic. Improvements in this technology have driven all subsequent improvements in cost.

With the rise of [integrated circuits](http://en.wikipedia.org/wiki/Integrated_circuits), reducing the absolute number of chips used represented another way to save costs. The goal of a designer is not just to make the simplest circuit, but to keep the component count down. Sometimes this results in slightly more complicated designs with respect to the underlying digital logic but nevertheless reduces the number of components, board size, and even power consumption.

For example, in some logic families, [NAND](http://en.wikipedia.org/wiki/NAND) gates are the simplest digital gate to build. All other logical operations can be implemented by NAND gates. If a circuit already required a single NAND gate, and a single chip normally carried four NAND gates, then the remaining gates could be used to implement other logical operations like [logical and](http://en.wikipedia.org/wiki/Logical_and). This could eliminate the need for a separate chip containing those different types of gates.

The "reliability" of a logic gate describes its mean time between failure (MTBF). Digital machines often have millions of logic gates. Also, most digital machines are "optimized" to reduce their cost. The result is that often, the failure of a single logic gate will cause a digital machine to stop working.

Digital machines first became useful when the MTBF for a switch got above a few hundred hours. Even so, many of these machines had complex, well-rehearsed repair procedures, and would be nonfunctional for hours because a tube burned-out, or a moth got stuck in a relay. Modern transistorized integrated circuit logic gates have MTBFs greater than 82 billion hours (8.2×1010) hours,[[5]](http://en.wikipedia.org/wiki/Digital_electronics#cite_note-4) and need them because they have so many logic gates.

Fanout describes how many logic inputs can be controlled by a single logic output without exceeding the current ratings of the gate.[[6]](http://en.wikipedia.org/wiki/Digital_electronics#cite_note-5) The minimum practical fanout is about five. Modern electronic logic using [CMOS](http://en.wikipedia.org/wiki/CMOS) transistors for switches have fanouts near fifty, and can sometimes go much higher.

The "switching speed" describes how many times per second an inverter (an electronic representation of a "logical not" function) can change from true to false and back. Faster logic can accomplish more operations in less time. Digital logic first became useful when switching speeds got above fifty [hertz](http://en.wikipedia.org/wiki/Hertz), because that was faster than a team of humans operating mechanical calculators. Modern electronic digital logic routinely switches at five [gigahertz](http://en.wikipedia.org/wiki/Gigahertz)(5×109 hertz), and some laboratory systems switch at more than a [terahertz](http://en.wikipedia.org/wiki/Terahertz) (1×1012 hertz).

### Logic families

Design started with [relays](http://en.wikipedia.org/wiki/Relay). Relay logic was relatively inexpensive and reliable, but slow. Occasionally a mechanical failure would occur. Fanouts were typically about ten, limited by the resistance of the coils and arcing on the contacts from high voltages.

Later, [vacuum tubes](http://en.wikipedia.org/wiki/Vacuum_tube) were used. These were very fast, but generated heat, and were unreliable because the filaments would burn out. Fanouts were typically five to seven, limited by the heating from the tubes' current. In the 1950s, special "computer tubes" were developed with filaments that omitted volatile elements like silicon. These ran for hundreds of thousands of hours.

The first [semiconductor](http://en.wikipedia.org/wiki/Semiconductor) logic family was [resistor-transistor logic](http://en.wikipedia.org/wiki/Resistor-transistor_logic). This was a thousand times more reliable than tubes, ran cooler, and used less power, but had a very low [fan-in](http://en.wikipedia.org/wiki/Fan-in) of three. [Diode-transistor logic](http://en.wikipedia.org/wiki/Diode-transistor_logic) improved the fanout up to about seven, and reduced the power. Some DTL designs used two power-supplies with alternating layers of NPN and PNP transistors to increase the fanout.

[Transistor transistor logic](http://en.wikipedia.org/wiki/Transistor_transistor_logic) (TTL) was a great improvement over these. In early devices, fanout improved to ten, and later variations reliably achieved twenty. TTL was also fast, with some variations achieving switching times as low as twenty nanoseconds. TTL is still used in some designs.

[Emitter coupled logic](http://en.wikipedia.org/wiki/Emitter_coupled_logic) is very fast but uses a lot of power. It was extensively used for high-performance computers made up of many medium-scale components ( such as the [Illiac IV](http://en.wikipedia.org/wiki/Illiac_IV)).

By far, the most common digital integrated circuits built today use [CMOS logic](http://en.wikipedia.org/wiki/CMOS), which is fast, offers high circuit density and low-power per gate. This is used even in large, fast computers, such as the [IBM System z](http://en.wikipedia.org/wiki/IBM_System_z).

**Building blocks:**

* [Logic gates](http://en.wikipedia.org/wiki/Logic_gate)
* [Adders](http://en.wikipedia.org/wiki/Adder_(electronics))
* [Flip-Flops](http://en.wikipedia.org/wiki/Flip-flop_(electronics))
* [Counters](http://en.wikipedia.org/wiki/Counter)
* [Registers](http://en.wikipedia.org/wiki/Processor_register)
* [Multiplexers](http://en.wikipedia.org/wiki/Multiplexer)
* [Schmitt triggers](http://en.wikipedia.org/wiki/Schmitt_trigger)

**Highly integrated devices:**

* [Microprocessors](http://en.wikipedia.org/wiki/Microprocessor)
* [Microcontrollers](http://en.wikipedia.org/wiki/Microcontroller)
* [Application-specific integrated circuit](http://en.wikipedia.org/wiki/Application-specific_integrated_circuit) (ASIC)
* [Digital signal processor](http://en.wikipedia.org/wiki/Digital_signal_processor) (DSP)
* [Field-programmable gate array](http://en.wikipedia.org/wiki/Field-programmable_gate_array) (FPGA)

[**Heat dissipation and thermal management**](http://en.wikipedia.org/wiki/Electronics#Heat_dissipation_and_thermal_management)

[Heat](http://en.wikipedia.org/wiki/Heat) generated by electronic circuitry must be dissipated to prevent immediate failure and improve long term reliability. Techniques for heat dissipation can include [heat sinks](http://en.wikipedia.org/wiki/Heat_sink) and [fans](http://en.wikipedia.org/wiki/Fan_(mechanical)) for air cooling, and other forms of [computer cooling](http://en.wikipedia.org/wiki/Computer_cooling) such as [water cooling](http://en.wikipedia.org/wiki/Water_cooling). These techniques use [convection](http://en.wikipedia.org/wiki/Convection), [conduction](http://en.wikipedia.org/wiki/Heat_conduction), & [radiation](http://en.wikipedia.org/wiki/Radiation) of heat energy.

[**Noise**](http://en.wikipedia.org/wiki/Electronics#Noise)

**Electronic noise**  is a random fluctuation in an electrical signal, a characteristic of all [electronic](http://en.wikipedia.org/wiki/Electronics) [circuits](http://en.wikipedia.org/wiki/Electrical_circuit). Noise generated by electronic devices varies greatly, as it can be produced by several different effects. [Thermal noise](http://en.wikipedia.org/wiki/Thermal_noise) is unavoidable at non-zero temperature (see [fluctuation-dissipation theorem](http://en.wikipedia.org/wiki/Fluctuation-dissipation_theorem)), while other types depend mostly on device type (such as [shot noise](http://en.wikipedia.org/wiki/Shot_noise),[[1]](http://en.wikipedia.org/wiki/Electronic_noise#cite_note-noise-0)[[2]](http://en.wikipedia.org/wiki/Electronic_noise#cite_note-shot-1) which needs steep potential barrier) or manufacturing quality and [semiconductor](http://en.wikipedia.org/wiki/Semiconductor) defects, such as conductance fluctuations, including [1/f noise](http://en.wikipedia.org/wiki/1/f_noise).

In [communication systems](http://en.wikipedia.org/wiki/Communication_system), the noise is an error or undesired random disturbance of a useful information signal, introduced before or after the detector and decoder. The noise is a summation of unwanted or disturbing energy from natural and sometimes man-made sources. Noise is, however, typically distinguished from [interference](http://en.wikipedia.org/wiki/Interference_(communication)), (e.g. [cross-talk](http://en.wikipedia.org/wiki/Cross-talk), deliberate[jamming](http://en.wikipedia.org/wiki/Radio_jamming) or other unwanted [electromagnetic interference](http://en.wikipedia.org/wiki/Electromagnetic_interference) from specific transmitters), for example in the [signal-to-noise ratio](http://en.wikipedia.org/wiki/Signal-to-noise_ratio) (SNR), [signal-to-interference ratio](http://en.wikipedia.org/wiki/Signal-to-interference_ratio) (SIR) and [signal-to-noise plus interference ratio](http://en.wikipedia.org/wiki/Signal_to_noise_plus_interference) (SNIR) measures. Noise is also typically distinguished from [distortion](http://en.wikipedia.org/wiki/Distortion), which is an unwanted alteration of the signal waveform, for example in the [signal-to-noise and distortion ratio](http://en.wikipedia.org/wiki/Signal-to-noise_and_distortion_ratio) (SINAD). In a carrier-modulated passband analog communication system, a certain [carrier-to-noise ratio](http://en.wikipedia.org/wiki/Carrier-to-noise_ratio) (CNR) at the radio receiver input would result in a certain[signal-to-noise ratio](http://en.wikipedia.org/wiki/Signal-to-noise_ratio) in the detected message signal. In a digital communications system, a certain [*E*b/*N*0](http://en.wikipedia.org/wiki/Eb/N0) (normalized signal-to-noise ratio) would result in a certain [bit error rate](http://en.wikipedia.org/wiki/Bit_error_rate) (BER).

While noise is generally unwanted, it can serve a useful purpose in some applications, such as [random number generation](http://en.wikipedia.org/wiki/Random_number_generation) or [dithering](http://en.wikipedia.org/wiki/Noise_(electronics)#Dither).

[***Quantification***](http://en.wikipedia.org/wiki/Electronic_noise#Quantification)

The **noise level** in an electronic system is typically measured as an electrical power *N* in [watts](http://en.wikipedia.org/wiki/Watt) or [dBm](http://en.wikipedia.org/wiki/Decibel), a [root mean square](http://en.wikipedia.org/wiki/Root_mean_square) (RMS) voltage (identical to the noise [standard deviation](http://en.wikipedia.org/wiki/Standard_deviation)) in volts, [dBμV](http://en.wikipedia.org/wiki/Decibel) or a [mean squared error](http://en.wikipedia.org/wiki/Mean_squared_error) (MSE) in volts squared. Noise may also be characterized by its [probability distribution](http://en.wikipedia.org/wiki/Probability_distribution) and [noise spectral density](http://en.wikipedia.org/wiki/Noise_spectral_density) *N*0(*f*) in watts per hertz.

A noise signal is typically considered as a linear addition to a useful information signal. Typical signal quality measures involving noise are [signal-to-noise ratio](http://en.wikipedia.org/wiki/Signal-to-noise_ratio) (SNR or *S*/*N*), [signal-to-quantization noise ratio](http://en.wikipedia.org/wiki/Signal-to-quantization_noise_ratio) (SQNR) in [analog-to-digital coversion](http://en.wikipedia.org/wiki/Analog_to_digital_converter) and compression, [peak signal-to-noise ratio](http://en.wikipedia.org/wiki/Peak_signal-to-noise_ratio) (PSNR) in image and video coding, [*E*b/*N*0](http://en.wikipedia.org/wiki/Eb/N0) in digital transmission, [carrier to noise ratio](http://en.wikipedia.org/wiki/Carrier_to_noise_ratio) (CNR) before the detector in carrier-modulated systems, and [noise figure](http://en.wikipedia.org/wiki/Noise_figure) in cascaded amplifiers.

Noise is a random process, characterized by [stochastic](http://en.wikipedia.org/wiki/Stochastic_process) properties such as its [variance](http://en.wikipedia.org/wiki/Variance), [distribution](http://en.wikipedia.org/wiki/Probability_distribution), and [spectral density](http://en.wikipedia.org/wiki/Spectral_density). The spectral distribution of noise can vary with [frequency](http://en.wikipedia.org/wiki/Frequency), so its power density is measured in watts per hertz (W/Hz). Since the power in a [resistive](http://en.wikipedia.org/wiki/Resistor) element is proportional to the square of the voltage across it, noise voltage (density) can be described by taking the square root of the noise power density, resulting in volts per root hertz (\scriptstyle \mathrm{V}/\sqrt{\mathrm{Hz}}). [Integrated circuit](http://en.wikipedia.org/wiki/Integrated_circuit) devices, such as [operational amplifiers](http://en.wikipedia.org/wiki/Operational_amplifiers) commonly quote[equivalent input noise](http://en.wikipedia.org/w/index.php?title=Equivalent_input_noise&action=edit&redlink=1) level in these terms (at room temperature).

Noise power is measured in Watts or [decibels](http://en.wikipedia.org/wiki/Decibel) (dB) relative to a standard power, usually indicated by adding a suffix after dB. Examples of electrical noise-level measurement units are[dBu](http://en.wikipedia.org/wiki/DBu), [dBm0](http://en.wikipedia.org/wiki/DBm0), [dBrn](http://en.wikipedia.org/wiki/DBrn), [dBrnC](http://en.wikipedia.org/wiki/DBrnC), and dBrn(*f*1 − *f*2), dBrn(144-[line](http://en.wikipedia.org/wiki/Line_(electrical_engineering))).

Noise levels are usually viewed in opposition to [signal levels](http://en.wikipedia.org/wiki/Signal_level) and so are often seen as part of a [signal-to-noise ratio](http://en.wikipedia.org/wiki/Signal-to-noise_ratio) (SNR). Telecommunication systems strive to increase the ratio of signal level to noise level in order to effectively transmit data. In practice, if the transmitted signal falls below the level of the noise (often designated as the [noise floor](http://en.wikipedia.org/wiki/Noise_floor)) in the system, data can no longer be decoded at the receiver. Noise in telecommunication systems is a product of both internal and external sources to the system.

[***Dither***](http://en.wikipedia.org/wiki/Electronic_noise#Dither)

f the noise source is correlated with the signal, such as in the case of [quantisation error](http://en.wikipedia.org/wiki/Quantisation_error), the intentional introduction of additional noise, called [dither](http://en.wikipedia.org/wiki/Dither), can reduce overall noise in the bandwidth of interest. This technique allows retrieval of signals below the nominal detection threshold of an instrument. This is an example of [stochastic resonance](http://en.wikipedia.org/wiki/Stochastic_resonance).

[**Electronics theory**](http://en.wikipedia.org/wiki/Electronics#Electronics_theory)

[***Mathematics in Electronics***](http://en.wikipedia.org/wiki/Mathematical_methods_in_electronics#Mathematics_in_Electronics)

Electrical Engineering careers usually include courses in [Calculus](http://en.wikipedia.org/wiki/Calculus) (single and [multivariable](http://en.wikipedia.org/wiki/Multivariable_Calculus)), [Complex Analysis](http://en.wikipedia.org/wiki/Complex_analysis), [Differential Equations](http://en.wikipedia.org/wiki/Differential_Equations) (both [ordinary](http://en.wikipedia.org/wiki/Ordinary_differential_equation) and [partial](http://en.wikipedia.org/wiki/Partial_differential_equation)), [Linear Algebra](http://en.wikipedia.org/wiki/Linear_Algebra) and[Probability](http://en.wikipedia.org/wiki/Probability). [Fourier Analysis](http://en.wikipedia.org/wiki/Fourier_Analysis) and [Z-Transforms](http://en.wikipedia.org/wiki/Z-transform) are also subjects which are usually included in electrical engineering programs.

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

[***Basic applications***](http://en.wikipedia.org/wiki/Mathematical_methods_in_electronics#Basic_applications)

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

* [Faraday's law of induction](http://en.wikipedia.org/wiki/Faraday%27s_law_of_induction): Any change in the magnetic environment of a coil of wire will cause a voltage (emf) to be "induced" in the coil.
* [Gauss's Law](http://en.wikipedia.org/wiki/Gauss%27s_law): The total of the electric flux out of a closed surface is equal to the charge enclosed divided by the permittivity.
* [Kirchhoff's current law](http://en.wikipedia.org/wiki/Kirchhoff%27s_circuit_laws#Kirchhoff.27s_current_law): the sum of all currents entering a node is equal to the sum of all currents leaving the node or the sum of total current at a junction is zero
* [Kirchhoff's voltage law](http://en.wikipedia.org/wiki/Kirchhoff%27s_circuit_laws#Kirchhoff.27s_voltage_law): the directed sum of the electrical potential differences around a circuit must be zero.
* [Ohm's law](http://en.wikipedia.org/wiki/Ohm%27s_law): the voltage across a resistor is the product of its resistance and the current flowing through it.at constant temperature.
* [Norton's theorem](http://en.wikipedia.org/wiki/Norton%27s_theorem): any two-terminal collection of voltage sources and resistors is electrically equivalent to an ideal current source in parallel with a single resistor.
* [Thevenin's theorem](http://en.wikipedia.org/wiki/Thevenin%27s_theorem): any two-terminal combination of voltage sources and resistors is electrically equivalent to a single voltage source in series with a single resistor.
* [Millman's theorem](http://en.wikipedia.org/wiki/Millman%27s_Theorem): the voltage on the ends of branches in parallel is equal to the sum of the currents flowing in every branch divided by the total equivalent conductance.
* See also [Analysis of resistive circuits](http://en.wikipedia.org/wiki/Analysis_of_resistive_circuits).

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

* [Circuit analysis](http://en.wikipedia.org/wiki/Circuit_analysis)

[***Components***](http://en.wikipedia.org/wiki/Mathematical_methods_in_electronics#Components)

There are many electronic components currently used and they all have their own uses and particular rules and methods for use.

* [Electronic components](http://en.wikipedia.org/wiki/Electronic_components)

[***Complex numbers***](http://en.wikipedia.org/wiki/Mathematical_methods_in_electronics#Complex_numbers)

A **complex number** is a [number](http://en.wikipedia.org/wiki/Number) consisting of a [*real*](http://en.wikipedia.org/wiki/Real_number) part and an [*imaginary*](http://en.wikipedia.org/wiki/Imaginary_number) part. Complex numbers extend the idea of the one-dimensional[number line](http://en.wikipedia.org/wiki/Number_line) to the two-dimensional [complex plane](http://en.wikipedia.org/wiki/Complex_plane) by using the number line for the real part and adding a vertical axis to plot the imaginary part. In this way the complex numbers [contain](http://en.wikipedia.org/wiki/Subfield) the ordinary real numbers while extending them in order to solve problems that would be impossible with only real numbers.

Complex numbers are [used](http://en.wikipedia.org/wiki/Complex_numbers#Applications) in many [scientific fields](http://en.wikipedia.org/wiki/Scientific_fields), including [engineering](http://en.wikipedia.org/wiki/Engineering), [electromagnetism](http://en.wikipedia.org/wiki/Electromagnetism), [quantum physics](http://en.wikipedia.org/wiki/Quantum_physics), [applied mathematics](http://en.wikipedia.org/wiki/Applied_mathematics), and[chaos theory](http://en.wikipedia.org/wiki/Chaos_theory). Italian mathematician [Gerolamo Cardano](http://en.wikipedia.org/wiki/Gerolamo_Cardano) is the first known to have introduced complex numbers; he called them "fictitious", during his attempts to find solutions to [cubic equations](http://en.wikipedia.org/wiki/Cubic_equations) in the 16th century.

[***Signal analysis***](http://en.wikipedia.org/wiki/Mathematical_methods_in_electronics#Signal_analysis)

* [Fourier analysis](http://en.wikipedia.org/wiki/Fourier_analysis). Deconstructing a [periodic](http://en.wikipedia.org/wiki/Wave) waveform into its constituent frequencies; see also: [Fourier theorem](http://en.wikipedia.org/wiki/Fourier_theorem), [Fourier transform](http://en.wikipedia.org/wiki/Fourier_transform).
* [Nyquist-Shannon sampling theorem](http://en.wikipedia.org/wiki/Nyquist-Shannon_sampling_theorem).
* [Information theory](http://en.wikipedia.org/wiki/Information_theory). Sets fundamental limits on how information can be transmitted or processed by any system.

[**Electronics lab**](http://en.wikipedia.org/wiki/Electronics#Electronics_lab)

**Electronic circuit simulation** uses mathematical models to replicate the behavior of an actual electronic device or circuit. Simulation software allows for modeling of circuit operation and is an invaluable analysis tool. Due to its highly accurate modeling capability, many [Colleges](http://en.wikipedia.org/wiki/Colleges) and [Universities](http://en.wikipedia.org/wiki/Universities) use this type of software for the teaching of [electronics technician](http://en.wikipedia.org/wiki/Electronics_technician) and[electronics engineering](http://en.wikipedia.org/wiki/Electronics_engineering) programs. Electronics simulation software engages the user by integrating them into the learning experience. These kinds of interactions actively engage learners to [analyze](http://en.wikipedia.org/wiki/Analyze), [synthesize](http://en.wikipedia.org/wiki/Synthesize), [organize](http://en.wikipedia.org/wiki/Organize), and evaluate content and result in learners constructing their own knowledge[[1]](http://en.wikipedia.org/wiki/Electronics_lab_simulation#cite_note-0).

Simulating a circuit’s behavior before actually building it can greatly improve design efficiency by making faulty designs known as such, and providing insight into the behavior of electronics circuit designs. In particular, for [integrated circuits](http://en.wikipedia.org/wiki/Integrated_circuits), the tooling ([photomasks](http://en.wikipedia.org/wiki/Photomask)) is expensive, [breadboards](http://en.wikipedia.org/wiki/Breadboard) are impractical, and probing the behavior of internal signals is extremely difficult. Therefore almost all [IC design](http://en.wikipedia.org/wiki/Integrated_circuit_design) relies heavily on simulation. The most well known analog simulator is [SPICE](http://en.wikipedia.org/wiki/SPICE). Probably the best known digital simulators are those based on [Verilog](http://en.wikipedia.org/wiki/Verilog) and [VHDL](http://en.wikipedia.org/wiki/VHDL).

Some electronics simulators integrate a [schematic editor](http://en.wikipedia.org/wiki/Schematic_editor), a simulation engine, and on-screen [waveforms](http://en.wikipedia.org/wiki/Waveforms) (see Figure 1), and make “what-if” scenarios easy and instant. They also typically contain extensive model and device libraries. These models typically include IC specific [transistor models](http://en.wikipedia.org/wiki/Transistor_models) such as BSIM, generic components such as [resistors](http://en.wikipedia.org/wiki/Resistor), [capacitors](http://en.wikipedia.org/wiki/Capacitor),[inductors](http://en.wikipedia.org/wiki/Inductor) and [transformers](http://en.wikipedia.org/wiki/Transformer), user defined models (such as controlled current and voltage sources, or models in [Verilog-A](http://en.wikipedia.org/wiki/Verilog-A) or [VHDL-AMS](http://en.wikipedia.org/wiki/VHDL-AMS)). [Printed circuit board](http://en.wikipedia.org/wiki/Printed_circuit_board) (PCB) design requires specific models as well, such as [transmission lines](http://en.wikipedia.org/wiki/Transmission_line) for the traces and [IBIS](http://en.wikipedia.org/wiki/IBIS_Interconnect_Modeling_Specification) models for driving and receiving electronics.

[***Types***](http://en.wikipedia.org/wiki/Electronics_lab_simulation#Types)

While there are strictly [analog](http://en.wikipedia.org/wiki/Analog_signal) [[2]](http://en.wikipedia.org/wiki/Electronics_lab_simulation#cite_note-1) electronics circuit simulators, popular simulators often include both analog and event-driven digital simulation[[3]](http://en.wikipedia.org/wiki/Electronics_lab_simulation#cite_note-2) capabilities, and are known as mixed-mode simulators [[4]](http://en.wikipedia.org/wiki/Electronics_lab_simulation#cite_note-3). This means that any simulation may contain components that are analog, event driven (digital or sampled-data), or a combination of both. An entire mixed [signal analysis](http://en.wikipedia.org/wiki/Signal_analysis) can be driven from one integrated schematic. All the digital models in mixed-mode simulators provide accurate specification of propagation time and rise/fall time delays.

The event driven [algorithm](http://en.wikipedia.org/wiki/Algorithm) provided by mixed-mode simulators is general purpose and supports non-digital types of data. For example, elements can use real or integer values to simulate DSP functions or sampled data filters. Because the event driven algorithm is faster than the standard SPICE matrix solution, simulation time is greatly reduced for circuits that use event driven models in place of analog models [[5]](http://en.wikipedia.org/wiki/Electronics_lab_simulation#cite_note-4).

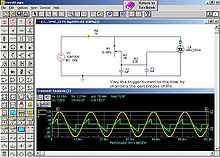
[](http://en.wikipedia.org/wiki/File:CircuitLogix3.jpg)Mixed-mode simulation is handled on three levels; (a) with primitive digital elements that use timing models and the built-in 12 or 16 state digital logic simulator, (b) with subcircuit models that use the actual transistor topology of the[integrated circuit](http://en.wikipedia.org/wiki/Integrated_circuit), and finally, (c) with In-line [Boolean logic](http://en.wikipedia.org/wiki/Boolean_logic) expressions. An example of a mixed-mode simulator is shown in Figure 2.

Figure 2. [CircuitLogix](http://en.wikipedia.org/wiki/CircuitLogix) mixed-mode simulator.

Exact representations are used mainly in the analysis of [transmission line](http://en.wikipedia.org/wiki/Transmission_line) and [signal integrity](http://en.wikipedia.org/wiki/Signal_integrity) problems where a close inspection of an IC’s I/O characteristics is needed. Boolean logic expressions are delay-less functions that are used to provide efficient logic signal processing in an analog environment. These two modeling techniques use SPICE to solve a problem while the third method, digital primitives, use mixed mode capability. Each of these methods has its merits and target applications. In fact, many simulations (particularly those which use A/D technology) call for the combination of all three approaches. No one approach alone is sufficient.

Another type of simulation used mainly for [power electronics](http://en.wikipedia.org/wiki/Power_electronics) represent [piecewise linear](http://en.wikipedia.org/wiki/Piecewise_linear)[[6]](http://en.wikipedia.org/wiki/Electronics_lab_simulation#cite_note-5) algorithms. These algorithms use an analog (linear) simulation until a [power electronic](http://en.wikipedia.org/wiki/Power_electronics) switch changes its state. At this time a new analog model is calculated to be used for the next simulation period. This methodology both enhances simulation speed and stability significantly

[***Complexities***](http://en.wikipedia.org/wiki/Electronics_lab_simulation#Complexities)

Often circuit simulators do not take into account the process variations that occur when the design is fabricated into silicon. These variations can be small, but taken together can change the output of a chip significantly.

[Process variations](http://en.wikipedia.org/wiki/Process_variation) occur in the manufacture of circuits in silicon.

Temperature variation can also be modeled to simulate the circuit's performance through temperature ranges.

[**Computer aided design (CAD)**](http://en.wikipedia.org/wiki/Electronics#Computer_aided_design_.28CAD.29)

Today's electronics engineers have the ability to [design](http://en.wikipedia.org/wiki/Circuit_design) [circuits](http://en.wikipedia.org/wiki/Electronic_circuit) using premanufactured building blocks such as [power supplies](http://en.wikipedia.org/wiki/Power_supply), [semiconductors](http://en.wikipedia.org/wiki/Semiconductor) (such as [transistors](http://en.wikipedia.org/wiki/Transistor)), and [integrated circuits](http://en.wikipedia.org/wiki/Integrated_circuit). [Electronic design automation](http://en.wikipedia.org/wiki/Electronic_design_automation) software programs include [schematic capture](http://en.wikipedia.org/wiki/Schematic_capture) programs and [printed circuit board](http://en.wikipedia.org/wiki/Printed_circuit_board) design programs. Popular names in the EDA software world are NI Multisim, Cadence ([ORCAD](http://en.wikipedia.org/wiki/ORCAD)), Eagle PCB and Schematic, Mentor (PADS PCB and LOGIC Schematic), Altium (Protel), LabCentre Electronics (Proteus), gEDA, KiCad and many others.

[**Construction methods**](http://en.wikipedia.org/wiki/Electronics#Construction_methods)

Many different methods of connecting components have been used over the years. For instance, early electronics often used [point to point wiring](http://en.wikipedia.org/wiki/Point-to-point_construction) with components attached to wooden breadboards to construct circuits. [Cordwood construction](http://en.wikipedia.org/wiki/Printed_circuit_board#.22Cordwood.22_construction) and [wire wraps](http://en.wikipedia.org/wiki/Wire_wrap) were other methods used. Most modern day electronics now use [printed circuit boards](http://en.wikipedia.org/wiki/Printed_circuit_board) made of materials such as [FR4](http://en.wikipedia.org/wiki/FR-4), or the cheaper (and less hard-wearing) Synthetic Resin Bonded Paper ([SRBP](http://en.wikipedia.org/wiki/SRBP), also known as Paxoline/Paxolin (trade marks) and FR2) - characterised by its light yellow-to-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](http://en.wikipedia.org/wiki/Restriction_of_Hazardous_Substances_Directive) (RoHS) and [Waste Electrical and Electronic Equipment Directive](http://en.wikipedia.org/wiki/Waste_Electrical_and_Electronic_Equipment_Directive) (WEEE), which went into force in July 2006.