Introduction to Electronic Circuits and Components

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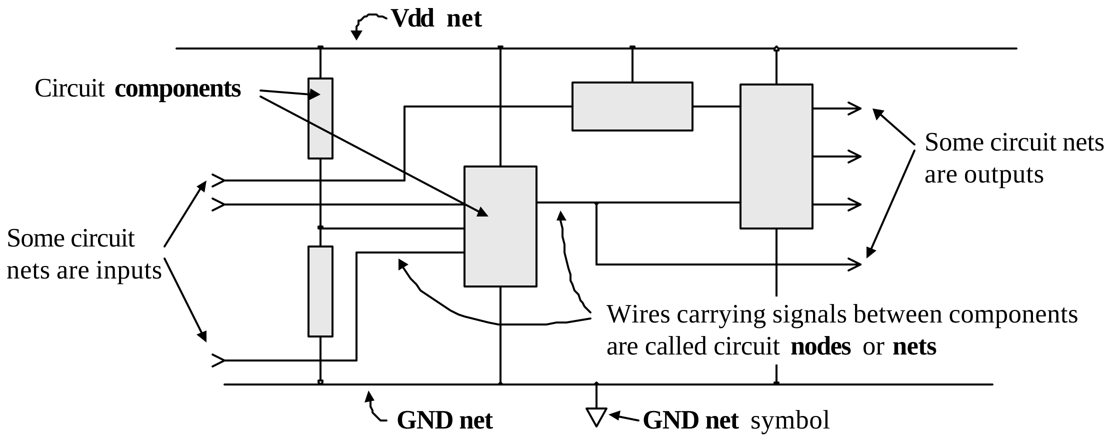
Overview

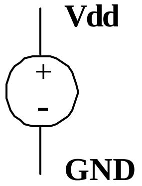
This document presents some introductory information targeted at those encountering electronic systems for the first time. Concepts and terminology are introduced in a non-rigorous, intuitive fashion, and they are limited to a few basics that precede a study of digital logic systems.

Electronic Circuits: Introductory Information

A collection of electronic components that have been assembled and interconnected to perform a given function is commonly referred to as a **circuit**. The word circuit derives from the fact that electric power must flow from the positive terminal of a power source through one or more electronic devices and back to the negative terminal of a power source, thereby forming a circuit. If the connections between an electronic device and either the positive or negative terminals of a power supply are severed, the circuit will be broken and the device will not function. Many different types of electronic devices can be found in modern circuits, including resistors, capacitors, inductors, and semiconductor devices (common semiconductor devices include diodes, transistors, and integrated circuits). These devices are discussed later in this document. Devices in a circuit are connected to one another by means of electrical conductors, or wires. These wires can move electric signals between various points in a circuit. Once a wire connects two or more devices, the wire and all attached device connectors are said to form a single circuit **node** or **net**. Any electrical activity on a given net is communicated to all devices attached to the net. Certain nets provide electric power to devices, and other nets carry information between devices. Some nets provide circuit inputs from the "outside world"; these input nets are generally shown entering the left side of component and/or the overall schematic. Other nets present circuit outputs to the outside world; these nets are generally shown on the right. In the sample schematic below, circuit components are shown as arbitrary shapes, nets are shown as lines, and inputs and outputs are denoted by connector symbols.



Schematic representation of an electric circuit.



Schematic representation of a power supply. Even if not shown, its presence is always assumed when circuit nodes are labeled Vdd and GND.

A circuit requires a **power supply** to provide a constant and stable source of electric power to all devices. Electric power is derived from the basic electrical forces that charged particles (e.g., protons and electrons) exert on one another – namely, negative particles repel negative particles but attract positive particles. The vast majority of charged particles are found in ordinary matter bound in electrically neutral atomic structures (that is, most particles are found in structures that have an equal number of positive and negative particles). A power supply is a local, contained imbalance of charged particles, with groups of negative and positive particles held in close proximity but separated by a barrier. This arrangement creates a source of usable electric force that can be harnessed to do useful work in a given circuit (turning a motor, heating an element, lighting a lamp, communicating information over a wire, etc.). A circuit allows the positive and negative particles contained in a power supply to recombine, but only via the paths designed into the circuit. It may be helpful to view an electric power supply as a water tank, and a circuit as a set of pipes, valves, and useful devices such as water wheels. In this analogy, the force of gravity acting on the water represents the electric force between charged particles, and the flow of water represents the flow of charged particles.

The basic unit of charge is the **Coulomb**. A single electron is said to have 1.602 x 10^{-19} Coulombs of charge, and one Coulomb contains 1.602 x 10^{19} electrons. The electric force between charged particles will cause unbound particles to move – positively charged particles towards negatively charged particles (or away from other positively changed particles), and vice-versa. The movement of charged particles is called electric current, and it is measured in **Amperes** (or amps). For our purposes, we will only consider charged particles moving in an electrical conductor or wire. One amp of current is equal to one Coulomb of particles passing a given point in one second. All conductors exhibit some resistance to the flow of electric current due to the moving particles colliding with the stationary particles that make up the conductor itself. Resistance to the flow of electric current is measured in **ohms**. An electric force is required to move electric current in the presence of resistance, and that force is none other than the force that exists between charged particles. The electric force is measured in **volts**, and one volt is defined by the amount of force required to move 1 amp of current through 1 ohm of resistance. This seemingly circular argument can be made more intuitive through application of the water analogy. The “voltage” in a water system is derived from some amount of water being held at some height above ground; “resistance” is derived from the diameter of pipes; and current is measured as the amount of water flowing past a given point in one second. Note that with both water circuits and electric circuits, the matter that creates an usable force is the same matter that flows as current in the circuit. A famous and foundational law called **Ohm’s law** relates voltage, current and resistance. Ohm’s law states simply that **V = IR** (where V is for Volts, I is for current, and R is for resistance), which means that if any two of the quantities of voltage, current, or resistance are known, the third can be easily found.

A power supply contains a plentiful supply of positively and negatively charged particles that are available for delivery to a circuit. A power supply’s output is characterized by the magnitude of force it can produce (volts), and the number of particles it can deliver in a given time period (amperes). The voltage and current that a given supply can produce is determined by a number of factors, including the quantity of particles that can be stored, their separation distance, the properties of the barrier between the particles, and several other factors. In a **digital** circuit, power supply voltage levels are constrained to two distinct values – “logic high voltage” (called **LHV** or **Vdd** for reasons that will be explained later) and “logic low voltage” (called **LLV** or **GND**). In general, the GND node in a digital circuit is the lowest voltage in the circuit, and all nodes labeled GND are tied together into the same node. Likewise, the Vdd node is the highest voltage in the circuit, and all nodes labeled Vdd are tied together into the same node. Vdd may be thought of as the “source” of positive charges in a circuit, and GND may be thought of as the “source” of negative charges in a circuit. In modern digital systems, Vdd and GND are separated by anywhere from 2 to 5 volts. Older or inexpensive circuits typically use 5 volts, while newer circuits use 1-3 volts. In digital circuits, the Vdd and GND voltages are used not only to supply electric power to circuit devices, they are used to represent information as well.

It is the flow of electric current that actually does work in electric circuits. When current flows through the windings of an electric motor, a magnetic field is created that can turn a shaft. When current flows through a resistive element, heat or light is produced. In a digital circuit, electric current carries charged particles along wires to and from various circuit nodes, causing either Vdd or GND to move among the various circuit components. A **signal** is a circuit node that “carries” Vdd and GND voltages among various circuit elements. Since a digital signal is constrained to be at one of two voltages (either Vdd or GND), it must be in one of two binary states (either high or low), and it is said to carry one **b**inary dig**it** (or **bit**) of information. Thus, signals can carry bits of information (in the form of Vdd or GND voltage levels) around a digital circuit. These two distinct voltage levels can be assigned two distinct symbols; by convention, we borrow the numerical symbols “**0**” and “**1**”. Using such symbols allows the use of existing logical and numerical techniques to be applied to digital signals. For instance, an AND relationship can be logically described as “true” when all inputs are “true” (i.e., output Y <= “true” when inputs “A” and “B” and “C”… are all “true”). If we assign the symbol “1” to “true”, then the AND relationship yields a “1” when the inputs are all “1”, concisely demonstrated by the truth table. It is conventional to assign the symbol “1” to LHV and “0” to LLV, although not all printed materials follow this convention.

A	**B**	**Y**
0	0	0
0	1	0
1	0	0
1	1	1

2-input AND truth table

Often, groups of digital signals may be grouped together to form a logical entity called a **bus**. Because each signal on a bus can carry a “1” or a “0”, busses can carry **binary numbers**. For example, if a 4-bit bus is used to represent a 4-bit binary number, then the bus can “carry” a binary number from 0 to 15 (0000 to 1111).

In contrast to digital circuits, **analog** circuits use signals whose voltage levels are not constrained to two distinct levels, but instead can assume any value between Vdd and GND. Many input devices, particularly those using electronic sensors (e.g., microphones, cameras, thermometers, pressure sensors, motion and proximity detectors, etc.) produce analog voltages at their outputs. In modern electronic devices, it is likely that such signals will be converted to digital signals before they are used within the device. For example, a digital voice-memo recording device uses an analog microphone circuit to convert sound pressure waves into similar voltage waves on an internal circuit node. A special circuit called an **analog-to-digital converter**, or ADC, converts that analog voltage to a binary number that can be represented as a bus in a digital circuit. An ADC functions by taking samples of the input analog signal, measuring the magnitude of the input voltage signal (usually with reference to GND), and assigning a binary number to the measured magnitude. Once an analog signal has been converted to a binary number, a bus can carry that digital information around a circuit. In a similar manner, digital signals can be reconstituted into analog signals using a **digital-to-analog converter**. Thus, a binary number that represents a sample of an audio waveform can be converted to an analog signal that can, for example, drive a speaker. In general, analog signals are more sensitive to degradation over time or over transmission distance, and they can be more difficult to process in electronic circuits. It is because digital signals are more robust and easier to work with that electronics industries the world over have “gone digital”.

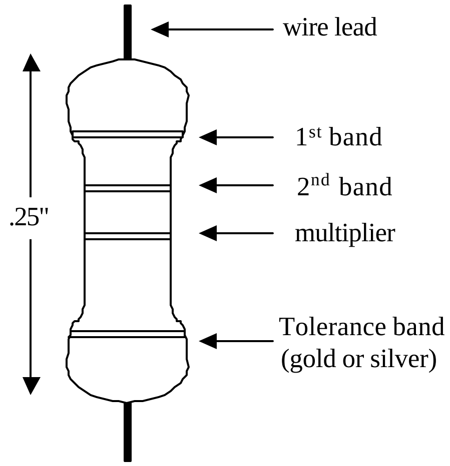
Electronic Components

Resistors

Resistors are two-terminal devices that restrict, or resist, the flow of current. The larger the resistor, the less current can flow through it for a given voltage as demonstrated by Ohm’s law. Electrons flowing through a resistor collide with material in the resistor body, and it is these collisions that cause electrical resistance. These collisions cause energy to be dissipated in the form of heat or light (as in a toaster or light bulb). Resistance is measured in Ohms, and an ohm is defined by the amount of resistance that causes 1A of current to flow from a 1V source. Resistors can be purchased in the range of about 1 ohm to several million ohms (or mega ohms). For most circuits, a one-ohm resistance is a relatively small value, and a 100KOhm resistance is a relatively large value. The physical size and appearance of a resistor is determined by the required application. Resistors that must dissipate large amounts of energy (such as in a toaster) are relatively large, whereas resistors that dissipate small amounts of current (such as those used on the Digilab board to set LED current) are relatively small. The amount of power (in Watts) dissipated in a resistor can be calculated using the equation $\mathbf{P=I^2R}$, where I is the current flowing through the resistor and R is the resistance. A resistor that can dissipate about 5 Watts of power would be about the size of a felt pen, and a resistor that can only dissipate ¼ Watt is about the size of a large grain of rice. If a resistor is placed in a circuit where it must dissipate more that its intended power, it will simply melt.

Several different resistors are used on Digilab boards. Some are used to limit the LED current, and some are used on inputs (like the button and switch circuits) to both limit the currents flowing to the main chip, and to protect against electrostatic discharge (or ESD – more on this topic later). The resistors on the Digilab boards, like most resistors used in digital systems, are physically small because they will not encounter large voltages or currents. For these smaller resistors, the resistor value in Ohms is encoded as a series of colored bands on the resistor body.

To determine the value of a small resistor (i.e., 1/8 Watt or 1/4 Watt), locate the tolerance band on one end of the resistor – it will typically be either gold (5% tolerance) or silver (10% tolerance). The color band at the other end of the resistor is band1. The table below shows the two-digit number associated with the colors of bands 1 and 2. The band nearest the tolerance band is the multiplier (or exponent) band. The digits associated with the first two color bands are multiplied by 10 raised to the power indicated by the color of the multiplier band. The following table associates band colors to digits and multiplier factors. Simply multiply the two-digit value by the multiplier, and you've got the resistor value. In circuit schematics and in parts lists, resistor reference designators always begin with an "R". You can see several rectangular white boxes with "R__" on the Digilab board silk-screen.



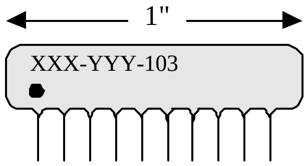
Resistor schematic symbol

Band Color	1st and 2nd band digits	Multiplier	Tolerance
Black	0	10^0	1%
Brown	1	10^1	2%
Red	2	10^2	3%
Orange	3	10^3	4%
Yellow	4	10^4	N/A
Green	5	10^5	N/A
Blue	6	10^6	N/A
Violet	7	10^7	N/A
Grey	8	10^8	N/A
White	9	10^9	N/A
Gold	N/A	.1	5%
Silver	N/A	.01	10%
No Color	N/A	N/A	20%

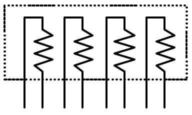
Resistor physical appearance, schematic symbol, and value chart

Resistor Packs

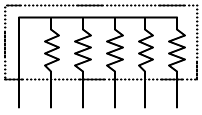
If a circuit application requires many resistors of the same value, and if those resistors can be located close together on a circuit board, then a resistor pack can be used instead of individual resistors. Resistors in a pack function identically to discrete resistors – they are just more economical to work with. Several different types of resistor packs are available. Two of the more common types, and the types used on the Digilab board, are called "bussed" packs and "isolated" packs. All resistors in a bussed resistor pack have one lead connected to a common node, while all resistors in an isolated pack have independent nodes (see the figures to the left.)



Resistor pack



Isolated pack



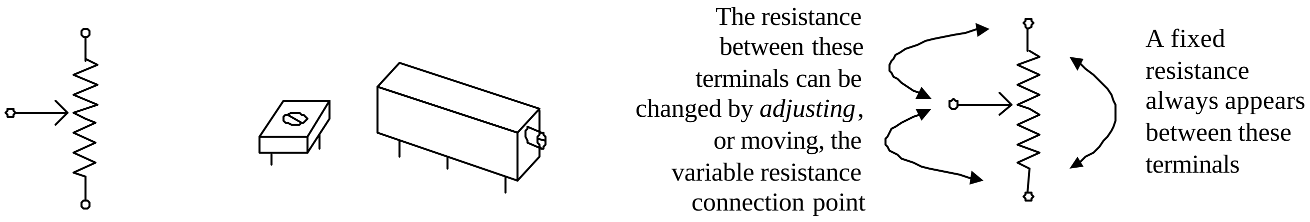
Bussed pack

Resistor values are also "encoded" on the pack body, but the code uses a three-digit number instead of colors. The first two digits are simply multiplied by 10^n, where n is the third digit. For example, if "271" was printed on a resistor pack, the resistors inside would be 270 ohms ($27 \times 10^1 = 270$). The three-digit number corresponding to resistor value is usually the last number (after the last dash) printed on the resistor pack. In circuit schematics, resistor packs are shown using the same jagged-line symbol as discrete resistors. On circuit board silk screens, they are typically shown as a narrow rectangular box. Reference designators are usually "R__" (like discrete resistors), or "RP__". On the Digilab board, the RP__ designator is used.

Variable Resistors

In some applications, it is either not possible or not convenient to use a fixed-value resistor. For example, it often occurs that some degree of precision is required in a circuit, but due to component variability, that precision cannot be assured. A variable resistor can be adjusted to calibrate such a circuit so that every circuit manufactured can meet specification. Or, a circuit may require an user adjustment such as speaker volume or operating frequency. A variable resistor can also serve this need.

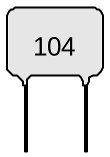
The most common variable resistors, also called potentiometers (or just “pots”), have three connections. Two connections offer a fixed resistance, and the third, user adjustable terminal offers a variable resistance when measured against either of the other two connections. The adjustable connection typically functions by physically moving a connection point in the resistive body. In small, inexpensive pots, turning a screw-contact either left or right makes the adjustment. The least expensive pots appear as smallish square plastic components (about 5mm square) with a screw terminal on them, and the variable resistance can be moved through all values by turning the adjustment through a single rotation. More expensive and more accurate pots require 15 or 20 turns to move the variable resistor through all possible values. These devices are in larger packages (about 20mm long x 5mm wide x 6mm tall), and typically feature a metal screw contact.



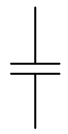
Variable resistor (or potentiometer) schematic symbol, appearance (single turn and 15-turn), and function

Capacitors

A capacitor is a two-terminal device that can store electric energy in the form of charged particles. You can think of a capacitor as a reservoir of charge that takes time to fill or empty. The voltage across a capacitor is proportional to the amount of charge it is storing – since it is not possible to instantaneously move charge to or from a capacitor, it is not possible to instantaneously change the voltage across a capacitor. It is this property that makes capacitors useful on the Digilab board and in many other applications.



Physical appearance of a resin-dipped metal-flim capacitor



Typcial schematic symbol for a capacitor

Capacitance is measured in **Farads**. A one Farad capacitor can store one Coulomb of charge at one volt. For engineering on a small scale (i.e., hand-held or desk-top devices), a one Farad capacitor stores far too much charge to be of general use (it would be like a car having a 1000 gallon gas tank). More useful capacitors are measured in micro-farads (uF) or **pico-farads** (pF). The terms "milli-farad" and "nano-farad" are rarely used. Large capacitors often have their value printed plainly on them, such as "10 uF" (for 10 microfards). Smaller capacitors, appearing as small disks or wafers, often have their values printed on them in an encoded manner (similar to the resistor packs discussed above). For these capacitors, a three-digit number indicates the capacitor value in pico-farads. The first two digits provide the "base" number, and the third digit provides an exponent of 10 (so, for example, "104" printed on a capacitor indicates a capacitance value of 10 x 10^4 or 100000 pF). Occasionally, a capacitor will only show a two-digit number, in which case that number is simply the capacitor value in pF. (To be complete, if a capacitor shows a three-digit number and the third digit is 8 or 9, then the first two digits are multiplied by .01 and .1 respectively). Often, a single letter is appended to the capacitance value – this letter indicates the quality of the capacitor.

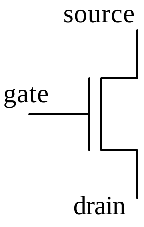
Capacitors are used on Digilab boards to keep the voltage supplies and some signals stable regardless of circuit activity, and to store charge when inputs are activated in order to slow their assertion times. The majority of the capacitors on the Digilab boards are used to **decouple** integrated circuits from the power supply. These **bypass** capacitors are placed on the board very close to the Vdd pins of all chips, where they can supply the short-term electrical current needs of the chips. Without such bypass capacitors, individual chips could cause the Vdd supply across the entire Digilab board to dip below 5V during times of heavy current demand. Nearly every chip in every digital system uses bypass capacitors. Bypass capacitor value can be determined if the worst-case current requirements are known (by using the formula $I = C\ \delta v/\delta t$), but more typically, capacitors in the range 0.01uF to 0.1uF are used without regard to the actual current requirements. The Digilab boards use 0.1uF bypass capacitors. The board also uses several **bulk bypass** capacitors located near the power supply to provide charge storage for the entire circuit board. These large 47uF capacitors can supply the individual bypass capacitors during times of exceptional need.

Depending on the size of the capacitor, the PCB silk screen will show either a circle or rectangle to indicate capacitor placement (usually, smallish capacitors are shown as rectangles, and larger capacitors as circles). Some capacitors are **polarized**, meaning they must be placed into the circuit board in a particular orientation (so that one terminal is never at a lower voltage than the other). Polarized capacitors either have a dark stripe near the pin that must be kept at a higher voltage, or a "-" near the pin that must be kept at a lower voltage. Silk-screen patterns for polarized capacitors will also often have a "+" sign nearest the through-hole that must be kept at a relatively higher voltage. Capacitors use a "C__" reference designator.

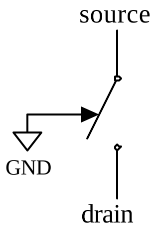
Transistors and Integrated Circuits

Transistors, in the simplest sense (which is how we will use them here) can be thought of as electrically controllable "on/off" switches. They are three-terminal devices, where one terminal is the control terminal (called the "**gate**" or "**base**" depending on the type of transistor) and the other two terminals may be thought of as the input and output. The two most common transistor types in use today are the MOSFETs (an acronym for Metal Oxide Semiconductor Field Effect Transistor) and BJTs (an acronym for Bipolar Junction Transistor). Both types are frequently used in modern digital circuits, but their different characteristics make them suitable for different applications. For example, MOSFETs require very little electric power to operate, they can be inexpensively manufactured in extremely small areas, and they can be switched on and off relatively quickly, so they are well suited for use in complex integrated circuits like microprocessors. Although this discussion will deal primarily with MOSFETs, the same general principles apply to BJTs as well.

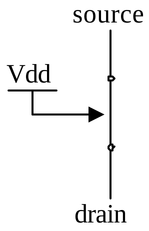
The input and output terminals of a MOSFET (or just FET) are called the **source** and the **drain**, and the control input is called the **gate**. An electrical connection is created between the source and the drain (i.e., the FET is turned “on”) when the gate input is **asserted**. One kind of FET, called an **nFET**, is turned on when Vdd is present at the control input, and a second type, called a **pFET**, is turned on when GND is present at the control input. Thus, an "asserted" input for an nFET means that the control signal is at Vdd, and for a pFET means the control input is at a GND. The figures below show the circuit symbols and equivalent switch diagrams for both nFETs and pFETs.



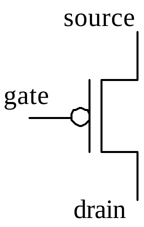
Circuit symbol used for an **nFET** in a schematic deawing



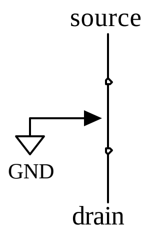
When the gate of an nFET is at GND, the nFET behaves like an **open switch**



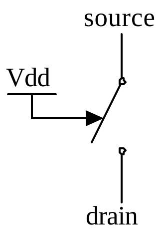
When the gate of an nFET is at Vdd, the nFET behaves like an **closed switch**



Circuit symbol used for a **pFET** in a schematic deawing



When the gate of a pFET is at GND, the pFET behaves like an **closed switch**



When the gate of a pFET is at Vdd, the pFET behaves like an **open switch**

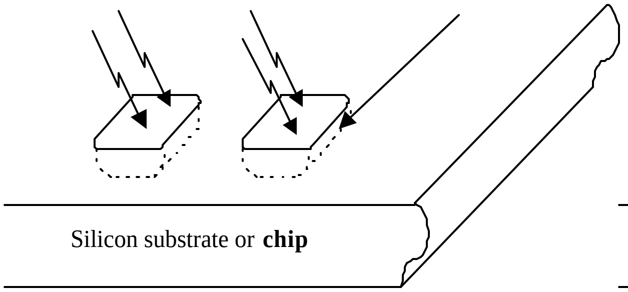
Individual FETs are often used as stand-alone electrically controllable on-off switches. As an example, if a pFET were used to turn on and off an appliance, then a power source might be connected to the source input, and a load (such as a motor, lamp, or other electrical component in an appliance) might be connected to the drain input. A signal applied to the gate could then turn the load device on (gate = GND) or off (gate = Vdd). Typically, a relatively small voltage (on the order of a few volts) is required to turn on a FET, even if the FET is switching large voltages and currents. Individual FETs used for this purpose are typically rather large (macroscopic) devices.

FETs can also be arranged into circuits that perform useful logic functions such as AND, OR, NOT, etc. In this application, several very small FETs are constructed on a single small piece of silicon (or **chip** of silicon) and then interconnected with equally small metal wires. These microscopic FETs typically occupy an area of less than 1 x $10e^{-7}m^{2}$. Since a silicon chip might measure several millimeters on a side, several millions of FETs can be constructed on a single chip. Circuits assembled in this fashion are said to form "integrated circuits" (or **IC’**s), because all circuit components are constructed and integrated on the same piece of silicon.

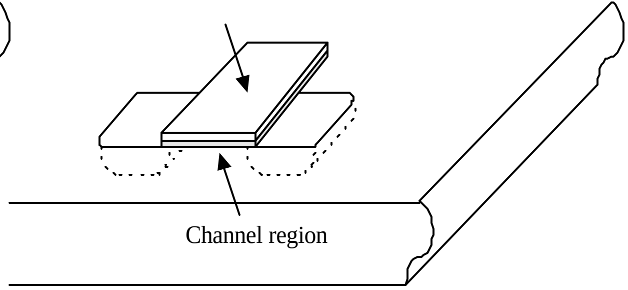
Most FETs are manufactured using the semi-conductor **silicon**. During manufacturing, a silicon chip is implanted with ions to make it more conductive in the areas that will become the FET source and the drain regions – these regions are commonly called **diffusion** regions. Next, a thin insulating layer is created between these diffusion regions, and another conductor is "grown" on top of this insulator. This grown conductor (typically silicon) forms the gate, and the area immediately under the gate and between the diffusion regions is called the **channel.** Finally, wires are connected to the source, drain, and gate structures so that the FET can be connected in a larger circuit. Several processing steps involving high temperatures, precise machine alignments, and various materials are required to produce transistors. Although a description of these processes is beyond the scope of this document, the processes are well documented and many very readable references exist (e.g. see the IBM website *http://www.chips.ibm.com/bluelogic/manufacturing/makechip/makechip1.html*).

Charged ions implanted in silicon in areas that will become FET source and drain

Source and drain diffusion regions are formed beneath the silicon surface

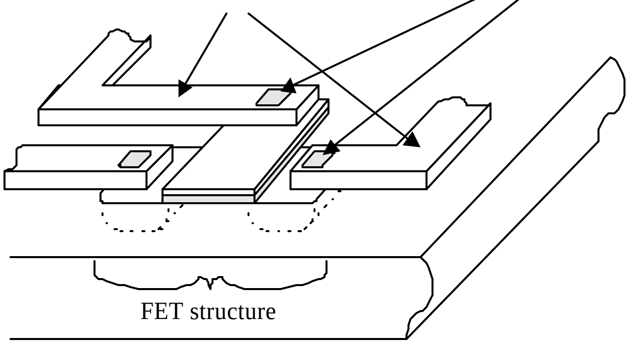


An insulator and conductor are grown in area between source and drain; this structure will form the FET's gate

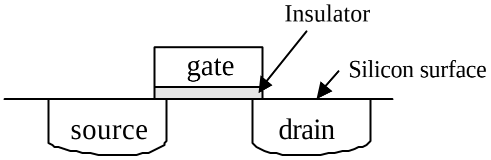


Metal wires are added to connect the source, drain, and gate to other circuit nodes.

Vias connect metal wires to diffusion and gate structures



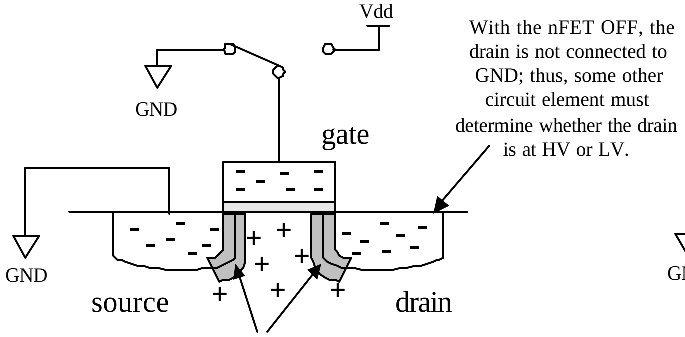
Cross-sectional view of FET



A FET device is symmetrical; we simply label one side the **source** and the other side the **drain**.

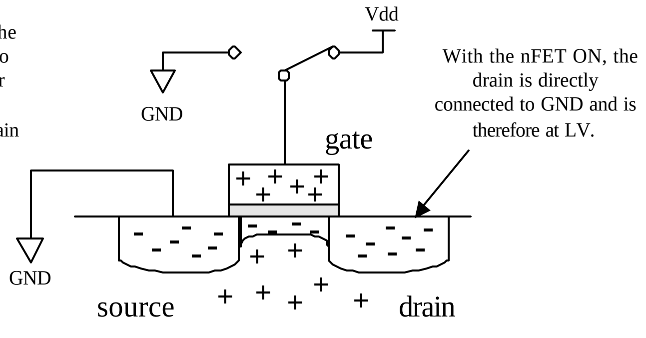
The basic principles of FET operation are actually quite straightforward. The following very basic discussion applies only to nFETs; pFET operation is entirely similar, but the voltages must be reversed. Refer to one of the many available texts for a more proper and detailed presentation of FET operation.

As the figure below shows, both the source and drain diffusion areas of an nFET are implanted with negatively charged particles. When an nFET is used in a logic circuit, its source lead is connected to GND, so that the nFET source, like the GND node, has an abundance of negatively charged particles. If the gate voltage of an nFET is at the same voltage as the source lead (i.e., GND), then the presence of the negatively charged particles on the gate repels negatively charged particles from the channel region immediately under the gate (note that in semiconductors such as silicon, positive and negative charges are mobile and can move about the semiconductor lattice under the influence of chargedparticle induced electric fields). A net positive charge accumulates under the gate, and two back-to-back positive-negative junctions of charge (called **pn junctions**) are formed. These pn-junctions prevent current flow in either direction. If the voltage on the gate is raised above the source voltage by an amount exceeding the **threshold** voltage (or $\mathbf{V_{th}}$, which equals about 0.5V), positive charges begin to accumulate on the gate and positive charges in the channel region immediately under the gate are repelled. A net negative charge accumulates under the gate, forming a **channel** of continuous conductive region in the area under the gate and between the source and drain diffusion areas. When the gate voltage reaches Vdd, a large conductive channel forms and the nFET is "strongly" on.



With the nFET OFF, the drain is not connected to GND; thus, some other circuit element must determine whether the drain is at HV or LV.

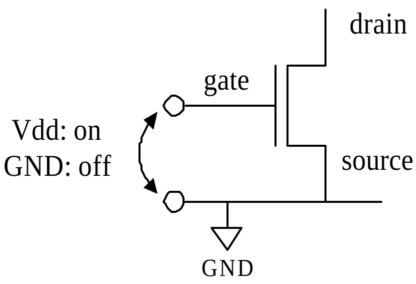
With the gate held at GND, back-to-back pn junctions are formed, current flow is prevented, and the nFET is **off**



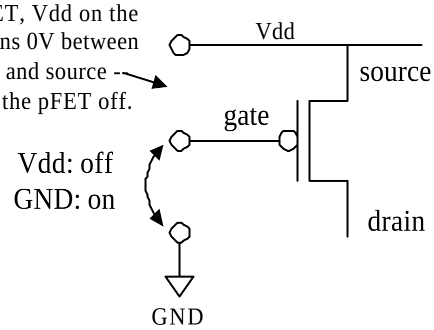
With the nFET ON, the drain is directly connected to GND and is therefore at LV.

With the at Vdd, a conductive channel of negatively charged particels forms under the gate and the nFET is **on**.

As the following figure shows, nFETs used in logic circuits have their source leads attached to GND and Vdd on their gate turns them on, while pFETs have their source leads attached to Vdd and GND on their gate turns them on.



In a pFET, Vdd on the gate means 0V between the gate and source -- turning the pFET off.



For reasons that will become clear later, an nFET with it's source attached to Vdd will not turn on very strongly, so nFET sources are rarely connected to Vdd. Similarly, a pFET with its source attached to GND will not turn on very well either, so pFETs are rarely connected to GND. Armed only with this basic description of FET operation, it is possible to construct the basic logic circuits that form the backbone of all digital and computer circuits. These logic circuits will combine one or more input signals to produce an output signal according to the logic function requirements. Shown below are the logical truth tables for the AND, OR, and NOT functions that will be used to guide logic circuit development. Note that the AND and OR truth tables can be extended to any number of inputs. These truth tables use 1's and 0's to show the logic relationships – in an actual circuit, the 1's and 0's are realized as logic signals at Vdd and GND.

AND
truth table

A	B	Y
0	0	0
0	1	0
1	0	0
1	1	1

OR
truth table

A	B	Y
0	0	0
0	1	1
1	0	1
1	1	1

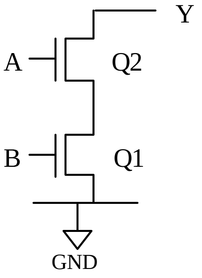
NOT
truth table

A	Y
0	1
1	0

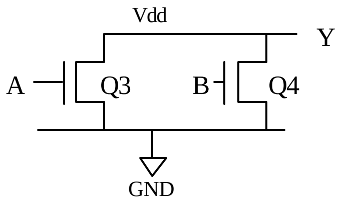
Electronic circuits that can implement logic relationships can be built of FETs. When building such circuits, four basic rules must be followed:

- pFET sources must be connected to Vdd and nFET sources must be connected to GND;
- the circuit output must always be connected to Vdd via an "on" pFET or to GND via an "on" nFET;
- the logic circuit output must never be connected to both Vdd and GND at the same time;
- and the circuit must use the fewest possible number of FETs.

Following these rules, a circuit that can form the AND relationship between two input signals is developed. But first, note that in the circuit on the left below, the output (labeled Y) is connected to GND only if the two inputs A *and* B are at Vdd. The two nFETs labeled Q1 and Q2 are said to be in **series**; in general, a series connection of FETs is required for an AND function. In the circuit on the right below, the output Y is connected to GND if A *or* B are at Vdd. The two nFETs labeled Q3 and Q4 are said to be in **parallel**; in general, a parallel connection of FETs is required for an OR function.

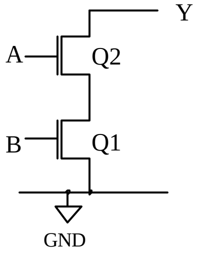


Series AND
configuration

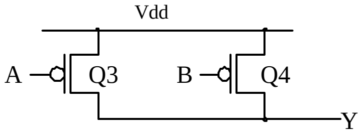


Parallel OR
configuration

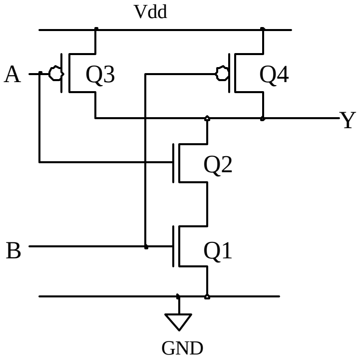
Keeping in mind the rules for FET logic circuits, an AND structure is created from Q1 and Q2 below. Using just these two FETs, Y is driven to GND whenever A ***and*** B are at Vdd. But we must also ensure the output Y is at Vdd when A and B are *not* both at Vdd; restated, we must ensure the output Y is at Vdd whenever A ***or*** B are at GND. This can be accomplished with an OR'ing structure of pFETs (Q3 and Q4 below). The AND'ing structure and OR'ing structure are assembled in the circuit on the right below. The adjacent operation table shows the input and output voltages for all four possible combinations of inputs. Note that this circuit obeys all the rules above – pFETs are connected only to Vdd, nFETs are connected only to ground, the output is always driven to Vdd or to GND but never to both simultaneously, and the fewest possible number of FETs are used.



Y <= GND when
A and B = Vdd



Y <= Vdd when
A or B = GND



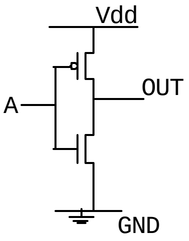
Y <= GND **iff**
A and B = Vdd;
else Y <= GND

A	B	Y
GND	GND	Vdd
GND	Vdd	Vdd
Vdd	GND	Vdd
Vdd	Vdd	GND

Operation table

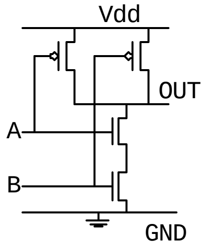
This AND'ing circuit has the interesting property of producing an output signal at ***GND*** when both inputs A and B are at ***Vdd***. In order to have this circuit's performance match the AND logical truth table above, we must associate an input signal at Vdd with a logic 1 (and therefore, an input signal at GND must be associated with a logic 0); and we must associate an output signal at GND with a logic 1.This creates a potentially confusing situation – considering the "1" symbol to represent a signal at Vdd on the input of a gate, and then considering that same "1" symbol to represent a signal at GND on the output of a gate. Note that if the outputs in the Y column of the truth table were **inverted** (that is, if Vdd were changed to GND and GND were changed to Vdd), then a "1" symbol could represent Vdd for both the inputs and outputs, resulting in the AND truth table presented earlier. Because of this, the circuit shown above is called a NOT AND gate (were NOT means inversion), which is shortened to "NAND" gate. To create an AND circuit in which both the input signals and output signals can associate a Vdd signal with a logic "1", an inverter circuit must be added to the output of the NAND gate. As the name implies, an inverter produces a Vdd output for a GND input, and vice-versa. Shown below are the five basic logic circuits: NAND, NOR (for "NOT OR"), AND, OR and INV (for inverter). The reader should verify that all truth tables show the correct circuit operation. These basic logic circuits are frequently referred to as **logic gates**.

In each of these circuits, the minimum number of FETs has been used to produce the required logic function. Each circuit has nFETs "on the bottom" and pFETs "on the top" performing complementary operations; that is, when an OR relationship is present in the nFETs, an AND relationship is present in the pFETs. FET circuits that exhibit this complementary nature are called Complementary Metal Oxide Semiconductor, or CMOS, circuits. CMOS circuits are by far the dominant circuits used today in digital and computer circuits. (Incidentally, the **M**etal-**O**xide-**S**emiconductor name refers to older technologies where the gate material was made of **m**etal and the insulator beneath the gate made of silicon **o**xide). These basic logic circuits form the basis for all digital and computer circuits.



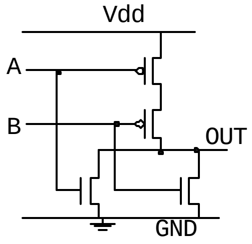
A	OUT
GND	Vdd
Vdd	GND

CMOS INVERTER



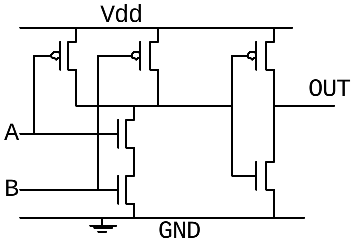
A	B	OUT
GND	GND	Vdd
GND	Vdd	Vdd
Vdd	GND	Vdd
Vdd	Vdd	GND

CMOS NAND



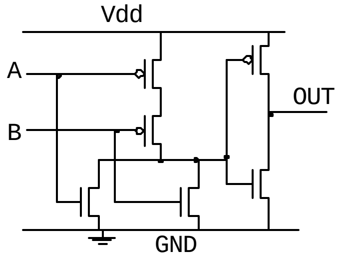
A	B	OUT
GND	GND	Vdd
GND	Vdd	GND
Vdd	GND	GND
Vdd	Vdd	GND

CMOS NOR



A	B	OUT
GND	GND	GND
GND	Vdd	GND
Vdd	GND	GND
Vdd	Vdd	Vdd

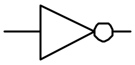
CMOS AND

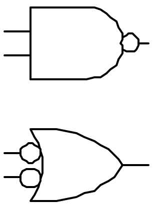


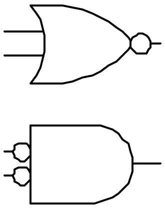
A	B	OUT
GND	GND	GND
GND	Vdd	Vdd
Vdd	GND	Vdd
Vdd	Vdd	Vdd

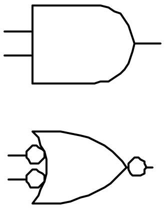
CMOS OR

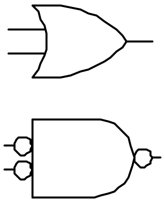
When these circuits are used in schematic drawings, well-defined shapes are used rather than the FET circuits (it would simply be too tedious to draw the FET circuits). Those shapes are also shown below. Note that a straight edge on the input side and smoothly curved output side means AND, while a curved edge on the input side and pointed output side means OR. Note also that a bubble on an input means that inputs must be at GND to produce the indicated logic function, and that a bubble on the output means that a GND output signal is produced as a result of the logic function. (The lack of a bubble on inputs means that signals must be at Vdd to produce the indicated function, and the lack of a bubble on the output means that a Vdd signal is produced as a result of the logic function.)


INV


NAND


NOR


AND

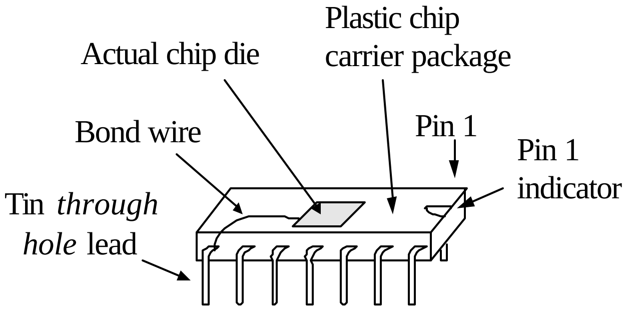

OR

Note that each of the symbols above has two appearances. The symbols on the top may be considered the primary symbols, and those on the bottom may be considered the **conjugate** symbols (properly, each symbol is the conjugate of the other). The reader should verify that the "bubble-GND / no-bubble Vdd" rule presented above holds for either symbol in a pair. For example, examine the OR-shaped NAND symbol and the NAND operation table, and verify that if the A or B input signals are at GND, then the output is at Vdd.

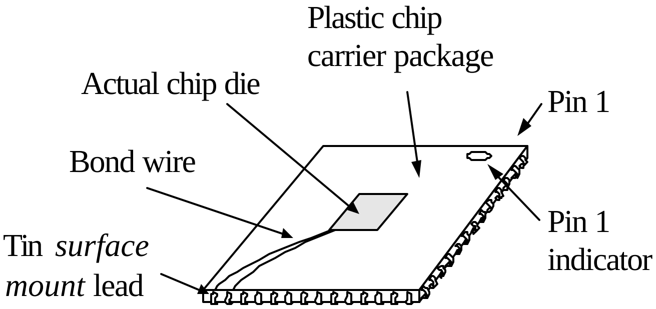
The terms **chip** and **integrated circuit** refer to FET circuits using microscopic transistors that are all co-located on the same small piece of silicon. Chips have been designed to do all sorts of functions, from very simple and basic logical switching functions to highly complex processing functions. Some chips contain just a handful of transistors, while others contain several million transistors. Some of the longest-surviving chips perform the most basic functions. These chips, denoted with the standard part numbers "74XXX", are simple small-scale integration devices that house small collections of logic circuits. For example, a chip known as a 7400 contains four individual NAND gates, with each input and output available at an external pin.

As shown in the figures below, the chips themselves are much smaller than their packages. During manufacturing, the small, fragile chips are glued (using epoxy) onto the bottom half of the package, bond-wires are attached to the chip and to the externally available pins, and then the top half of the chip package is permanently affixed. Smaller chips may only have a few pins, but larger chips can have more than 500 pins. Since the chips themselves are on the order of a centimeter on each side, very precise and delicate machines are required to mount them in their packages.

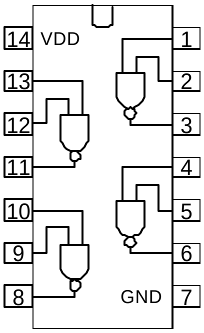
Smaller chips are usually packaged in a "DIP" package (DIP is an acronym for Dual In-line Package) as shown below. Typically on the order of 1" x 1/4", DIP packages are most often made from black plastic, and they can have anywhere from 8 to 48 pins protruding in equal numbers from either side. DIPs are used exclusively in through-hole processes. Larger chips use many different packages -- one common package, the "PLCC" (for Plastic Leaded Chip Carrier) is shown below. Since these larger packages can have up to several hundred pins, it is often not practical to use the relatively large leads required by through-hole packages. Thus, large chips usually use surface mount packages, where the external pins can be smaller and more densely packed.



DIP package



PLCC package



Shown on the right is a representation of a 7400 logic IC that contains 16 transistors organized as four 2-input NAND gates. This small chip is housed in a 14-pin DIP package that provides pins for each of the NAND gates inputs and outputs, as well as a power and ground pin (labeled Vdd and GND). Note the picture shows the four logic gates placed inside a DIP outline, thereby showing both the function and **pinout** (or pin definition) of the IC.

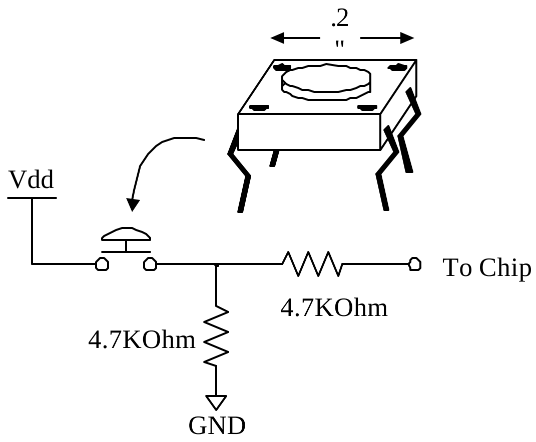
On schematics and on the circuit board, chips are often shown as square boxes denoted with a "U__" reference designator. Note that on the Digilab board, all the chips are loaded in sockets. Sockets are generally used when chips may need to be replaced or upgraded (such as older PC BIOS ROMs), or when chips are on a circuit board that might be damaged during frequent handling (such as the Digilab board). Chips, even in their plastic packages, are quite fragile are subject to damage from a variety of sources, including **electrostatic discharge** or **ESD**. Placing chips in sockets allows them to easily be replaced if they do get damaged.

When placing sockets in the PCB and later, chips into the sockets, **pin 1** must be correctly oriented. The circuit board silk screen, IC sockets, and the IC's themselves all indicate where pin 1 is located. For smaller chips and their sockets, a small **notch** is located on one end indicating pin 1 is to the immediate left. By convention, that same notch pattern appears in the circuit board silk screen. For larger IC's, either the corner of the IC nearest (and to the left) of pin 1 is shaved off, or a small indentation (or dot) is located at the corner nearest pin 1.

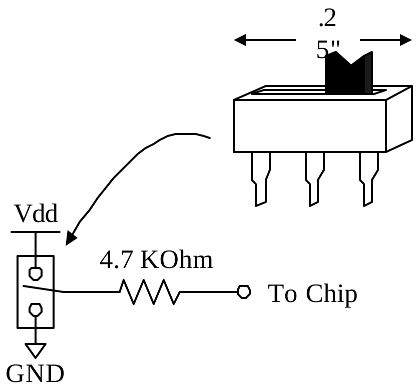
Input Devices (buttons and switches)

Circuits often require inputs that come directly from users (as opposed to inputs that come from other devices). Input devices can take many forms, among them keyboards (as on a PC), buttons (as on a calculator or telephone), rotary dials, switches and levers, etc. The Digilab board has twelve input devices, including four push buttons (BTN1 - BTN4) and eight slide-switches and (SW1 - SW8). Since digital circuits operate with two voltage levels (LHV or Vdd, and LLV or GND), input devices like buttons and switches should be able to produce both of these voltages based on some user action.

The slide switches are also known as "single throw-double pole" (STDP) switches, because only one switch (or throw) exists, but two positions (or poles) are available (a pole is an electrical contact to which the switch can make contact). These switches can be set to output either Vdd (when the actuator is closest to the board's edge) or GND. The push button switches are also known as "momentary" contact buttons, because they only make contact while they are actively being pressed – they output a GND at rest, and a Vdd only when they are being pressed.



Pushbutton and circuit used on Digilab boards

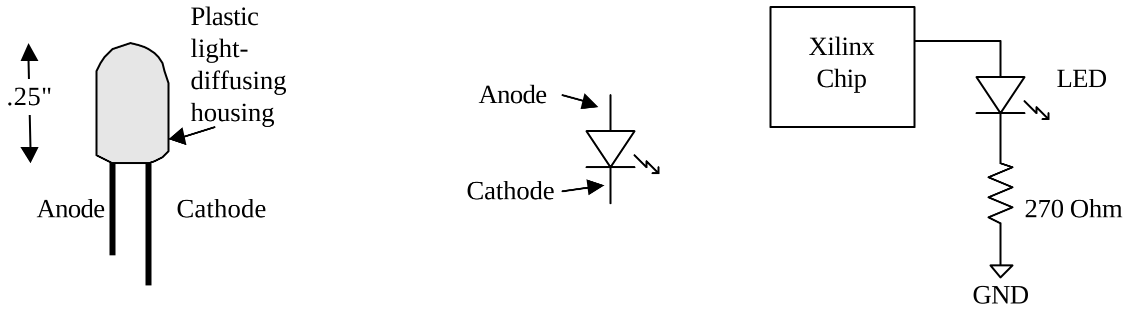


Slide switch and circuit used on Digilab boards

Output devices (LEDs)

Circuits often require output devices to communicate their state to an user. Examples of electronic output devices include computer monitors, LCD alphanumeric panels (as on a calculator), small lamps or light-emitting diodes (**LED**'s), etc. Outputs from the Digilab boards include individual LED's and seven-segment LED displays that can display the digits 0-9 in each digit position (each segment in the seven-segment display contains a single LED). LED's are two-terminal semiconductor devices that conduct current in only one direction (from the anode to the cathode). The small LED chips are secured inside a plastic housing, and they emit light at a given frequency (RED, YELLOW, etc.) when a small electric current (typically 10mA to 25mA) flows through them.

Individual LED's are denoted with an "LD__" reference designator on the Digilab boards, and the seven-segment display is denoted with a “DSP” reference designator. The LEDs and current limiting resistors are driven directly from the Xilinx chips, but the LED displays require the use of an external transistor to supply higher currents.

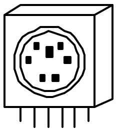


LED physical appearance, schematic symbol, and Digilab board circuit

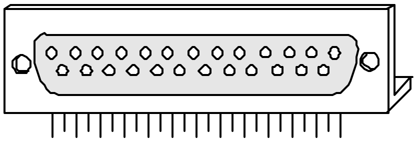
Connectors

The Digilab boards use several connectors for various purposes, but in general, they all communicate electronic information between the board and outside devices. By convention, connectors are given the reference designator "J__". Since connectors come in so many different sizes and shapes, they are usually shown on the PCB silk screen and on circuit schematics as just rectangular boxes.The following connectors are used on various Digilab boards (but not all connectors appear on all boards):

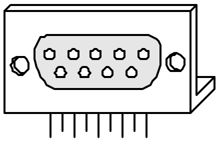
- The PS/2 connector allows connection to a mouse or keyboard;
- The DB25 connector allows a parallel cable to be attached for programming or data transfers;
- The DB9 port is used for RS-232 serial communications;
- The DB15 connector can be used to drive a VGA monitor;
- Various DIP sockets can be used to access various Xilinx chip connected signals;
- The power jack can accept any compatible DC power supply;
- The audio jack can be used to drive speakers or receive microphone inputs;
- And the BNC connector allows for easy connection of test and measurement equipment.



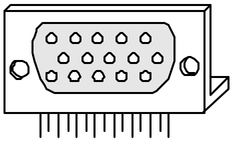
PS/2 connector



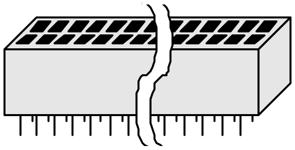
"DB25" Parallel port D-connector



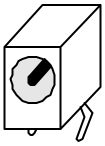
"DB9" Serial port D-connector



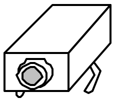
"DB15" VGA D-connector



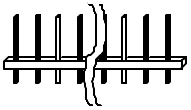
DIP sockets



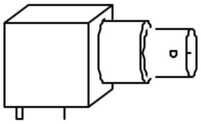
Power jack



Audio Jack



Headers

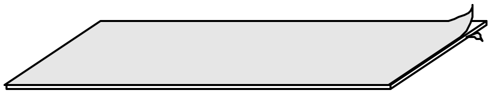


BNC connector

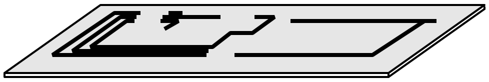
Printed Circuit Board (PCB)

Electronic components are often assembled and interconnected on a flat surface known as a circuit board. The several types of existing **circuit boards** may be divided into two broad categories: those intended for **prototype** or experimental circuits; and those intended for production and/or commercial sale. Circuit boards used for experimental work are often referred to as **breadboards** or **protoboards**. Breadboards allow engineers to construct circuits quickly, so that they can be studied and modified until an optimal design is discovered. In a typical breadboard use, components and wires are added to a circuit in an ad hoc manner as the design proceeds, with new data and new understanding dictating the course of the design. Since breadboard circuits exist only in the laboratory, no special consideration need be given to creating reliable or simple-to-manufacture circuits – the designer can focus exclusively on the circuit's behavior. In contrast, circuit boards intended for production or commercial sale must have highly reliable wires and interconnects, permanent bonds to all components, and topographies amenable to mass production and thorough testing. And further, they must be made of a material that is reliable, low-cost, and easy to manufacture. A fiberglass substrate with copper wires (etched from laminated copper sheets) has been the PCB material of choice for the past several decades. The Digilab board is a simple example of such a board. Note that most often, production circuit board designs are finalized only after extensive breadboard phases. Components are permanently affixed to production boards using the **soldering** process.

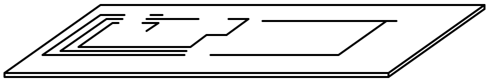
1) PCB begins as ~ 1mm thick fiberglass sheet



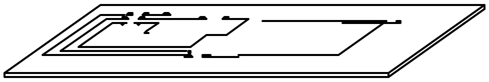
2) Thin copper sheets added to both sides



3) Etchant-resistive wire pattern printed on board



4) All copper removed except for wires and pads



5) Holes drilled for component leads and vias

Printed Circuit Board manufacturing steps

Production circuit boards typically start out as thin sheets of fiberglass (about 1mm thick) that are completely covered on both sides with very thin sheets of metal (typically copper). A "standard" circuit board might use a **1 ounce copper** process, which means that one ounce of copper is evenly spread across 1 square foot of circuit board. During the manufacturing process, wire patterns are "printed" onto the copper surfaces using a compound that resists etching (hence the name Printed Circuit Board or PCB). The boards are subjected to a chemical etching process that removes all exposed copper. The remaining, un-etched copper forms wires that will interconnect the circuit board components, and small **pads** that define the regions where component leads will be attached.

In a PCB that uses **through-hole** technology, holes are drilled through the pads so that component leads can be inserted and then fastened (soldered) in place. In a PCB that uses **surface-mount** technology, component leads are soldered directly to the pads on the surface. Each set of pads (or holes) in the PCB is intended to receive a particular component. To identify which component must be loaded where, **reference designators** are printed on the circuit board immediately adjacent to the pads using a silk-screen process. A **parts list** links a designated set of pads to a physical component by describing the component and assigning it a particular reference designator. The reference designators guide assemblers and testers when they are working with the PCB. Many components must be placed into the PCB in a particular orientation. By convention, components that require a particular orientation have one lead designated as **pin 1**. On the PCB, a **square pad** rather than the typical circular pad denotes pin 1.

On all but the simplest PCBs, wires must be printed on more than one surface of fiberglass to allow for all the required component interconnections. Each surface containing printed wires is called a **layer**. In a relatively simple PCB that requires only two layers, only one piece of fiberglass is required since wires can be printed on both sides. In a more complex PCB where several layers are required, individual circuit boards are manufactured separately and then laminated together to form one multi-layer circuit board. To connect wires on two or more layers, small holes called **vias** are drilled through the wires and fiberglass board at the point where the wires on the different layers cross. The interior surface of these holes is coated with metal so that electric current can flow through the vias. Most Digilab boards are simpler two or four layer boards; some more complex computer circuit boards have more than 20 layers.

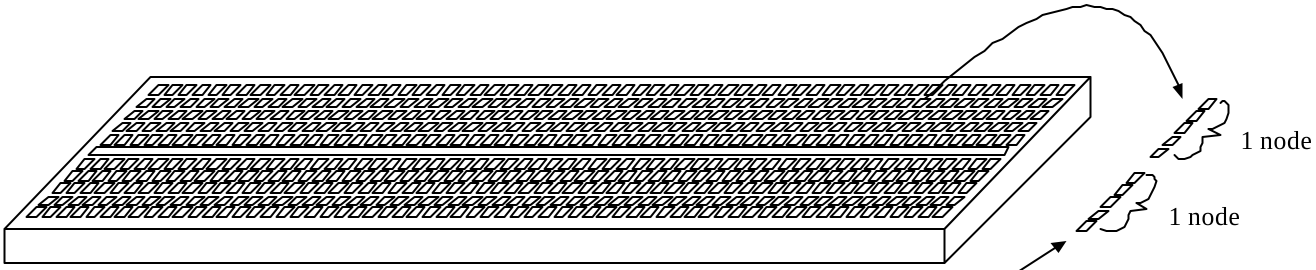
The unloaded PCB appears green because thin sheets of green plastic have been applied to both sides (otherwise the PCB would appear pale yellow). Called **solder masks**, these sheets cover all exposed metal other than the component pads and holes so that errant solder can't inadvertently **short** (or electrically connect) the printed wires. All metal surfaces other than the exposed pads and holes (i.e., the wires) are underneath the solder mask. Not infrequently, blue or even red solder masks are used.

Circuit components are manufactured with exposed metal **pins** (or **leads**) that are used to fasten them to the PCB both mechanically (so they won't fall off) and electrically (so current can pass between them). The **soldering** process, which provides a strong mechanical bond and a very good electrical connection, is used to fasten components to the PCB. During soldering, component leads are inserted through the holes in the PCB, and then the component leads and the through-hole plating metal are heated to above the melting point of the solder (about 500 to 700 degrees F). Solder (a metallic compound) is then melted and allowed to flow in and around the component lead and through-hole. The solder quickly cools to form a strong bond between the component and the PCB. The process of associating components with reference designators, loading them into their respective holes, and then soldering them in place comprises the PCB assembly process.

Examine the Digilab board, and note the printed wires on either side. Wires on one side go largely "north and south" while wires on the other side go largely "east and west". The perpendicular or **Manhattan** arrangement of wires on alternate layers is very common on multi-layer PCBs. Locate some vias, and note that they connect wires on opposite sides. Locate various components, their hole patterns, and associated reference designators. Identify pad 1 for the various components. Note that the through-holes are somewhat larger than the vias, and that component leads can easily be inserted into their through-holes, but not into vias.

Solderless breadboard

The solderless breadboard is a large, white plastic component with rows and columns of holes that provides a working space where temporary circuits can easily be built. Components (e.g., chips) can easily be pressed into the breadboard and then connected with bits of wire to other chips or to the circuit nodes available through the J2 connector. Solderless breadboards are very versatile and they can be used in the construction of several circuits.



Each row of 5 holes is electrically connected into the same circuit node; up to five component leads and/or wires can be connected