CHAPTER 3

Embedded Hardware Building Blocks and the Embedded Board

In This Chapter

- *Introducing the importance of being able to read a schematic diagram*
- *Discussing the major components of an embedded board*
- *Introducing the factors that allow an embedded device to work*
- *Discussing the fundamental elements of electronic components*

3.1 Lesson One on Hardware: Learn to Read a Schematic!

This section is especially important for embedded software engineers and programmers. Before diving into the details, note that it is important for ***all*** embedded designers to be able to understand the diagrams and symbols that hardware engineers create and use to describe their hardware designs to the outside world. These diagrams and symbols are the keys to quickly and efficiently understanding even the most complex hardware design, regardless of how much or little practical experience one has in designing real hardware. They also contain the information an embedded programmer needs to design any software that requires compatibility with the hardware, and they provide insight to a programmer as to how to successfully communicate the hardware requirements of the software to a hardware engineer.

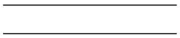
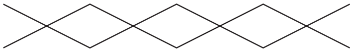
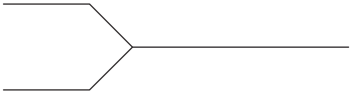
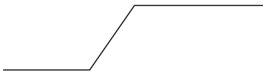
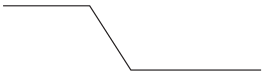
There are several different types of engineering hardware drawings, including:

- *Block diagrams*, which typically depict the major components of a board (processors, buses, I/O, memory) or a single component (a processor, for example) at a systems architecture or higher level. In short, a block diagram is a basic overview of the hardware, with implementation details abstracted out. While a block diagram can reflect the actual physical layout of a board containing these major components, it mainly depicts how different components or units within a component function together at a systems architecture level. Block diagrams are used extensively throughout this book (in fact, Figures 3-5a through 3-5e later in this chapter are examples of block diagrams), because they are the simplest method in which to depict and describe the components within a system. The symbols used within a block diagram are simple, such as squares or rectangles for chips, and straight lines for buses. Block diagrams are typically not detailed enough for a software designer to be able to write all of the low-level software accurately enough to control the hardware (without a lot of headaches, trial and error, and even some burned-out hardware!). However, they are very useful in communicating a basic overview of the hardware, as well as providing a basis for creating more detailed hardware diagrams.

- *Schematics.* Schematics are electronic circuit diagrams that provide a more detailed view of all of the devices within a circuit or within a single component—everything from processors down to resistors. A schematic diagram is not meant to depict the physical layout of the board or component, but provides information on the flow of data in the system, defining what signals are assigned where—which signals travel on the various lines of a bus, appear on the pins of a processor, and so on. In schematic diagrams, ***schematic symbols*** are used to depict all of the components within the system. They typically do not look anything like the physical components they represent but are a type of "shorthand" representation based on some type of schematic symbol standard. A schematic diagram is the most useful diagram to both hardware and software designers when trying to determine how a system actually operates, to debug hardware, or to write and debug the software managing the hardware. See Appendix B for a list of commonly used schematic symbols.
- *Wiring diagrams*. These diagrams represent the *bus* connections between the major and minor components on a board or within a chip. In wiring diagrams, vertical and horizontal lines are used to represent the lines of a bus, and either schematic symbols or more simplified symbols (that physically resemble the other components on the board or elements within a component) are used. These diagrams may represent an approximate depiction of the physical layout of a component or board.
- *Logic diagrams/prints*. Logic diagrams/prints are used to show a wide variety of circuit information using logical symbols (AND, OR, NOT, XOR, and so on), and logical inputs and outputs (the 1's and 0's). These diagrams do not replace schematics, but they can be useful in simplifying certain types of circuits in order to understand how they function.
- *Timing diagrams*. Timing diagrams display timing graphs of various input and output signals of a circuit, as well as the relationships between the various signals. They are the most common diagrams (after block diagrams) in hardware user manuals and data sheets.

Regardless of the type, in order to understand how to read and interpret these diagrams, it is first important to *learn* the standard **symbols**, **conventions**, and **rules** used. Examples of the symbols used in timing diagrams are shown in Table 3-1, along with the conventions for input/output signals associated with each of the symbols.

Table 3-1: Timing diagrams symbol table [3-9]

Symbol	Input Signals	Output Signals
	Input signal must be valid	Output signal will be valid
	Input signal doesn't affect system, will work regardless	Indeterminate output signal
	Garbage signal (nonsense)	Output signal not driven (floating), tristate, HiZ, high impedance
	If the input signal rises	Output signal will rise
	If the input signal falls	Output signal will fall

An example of a timing diagram is shown in Figure 3-1. In this figure, each row represents a different signal. In the case of the signal rising and falling symbols within the diagram, the *rise time* or *fall time* is indicated by the time it takes for the signal to move from LOW to HIGH or vice-versa (the entire length of the diagonal line of the symbol). When comparing two signals, a delay is measured at the center of the rising or falling symbols of each signal being compared. In Figure 3-1, there is a fall time delay between signals B and C and signals A and C in the first falling symbol. When comparing the first falling symbol of signals A and B in the figure, no delay is indicated by the timing diagram.

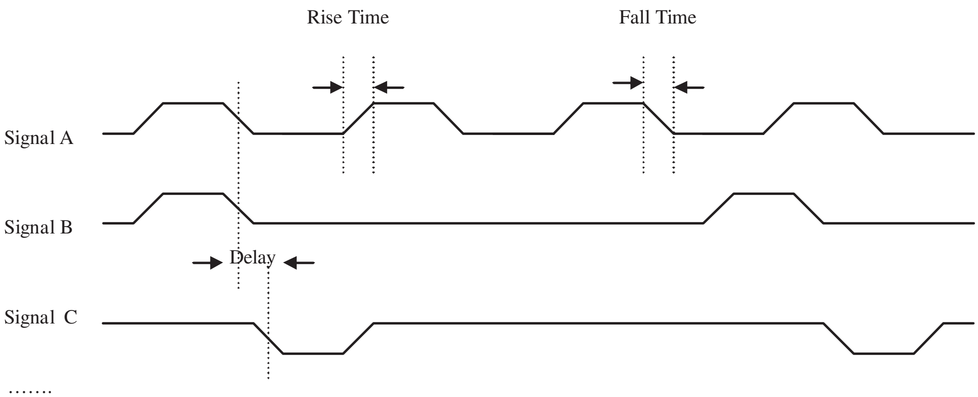


Figure 3-1: Timing diagram example

Schematic diagrams are much more complex than their timing diagram counterparts. As introduced earlier this chapter, schematics provide a more detailed view of all of the devices within a circuit or within a single component. Figure 3-2 shows an example of a schematic diagram.

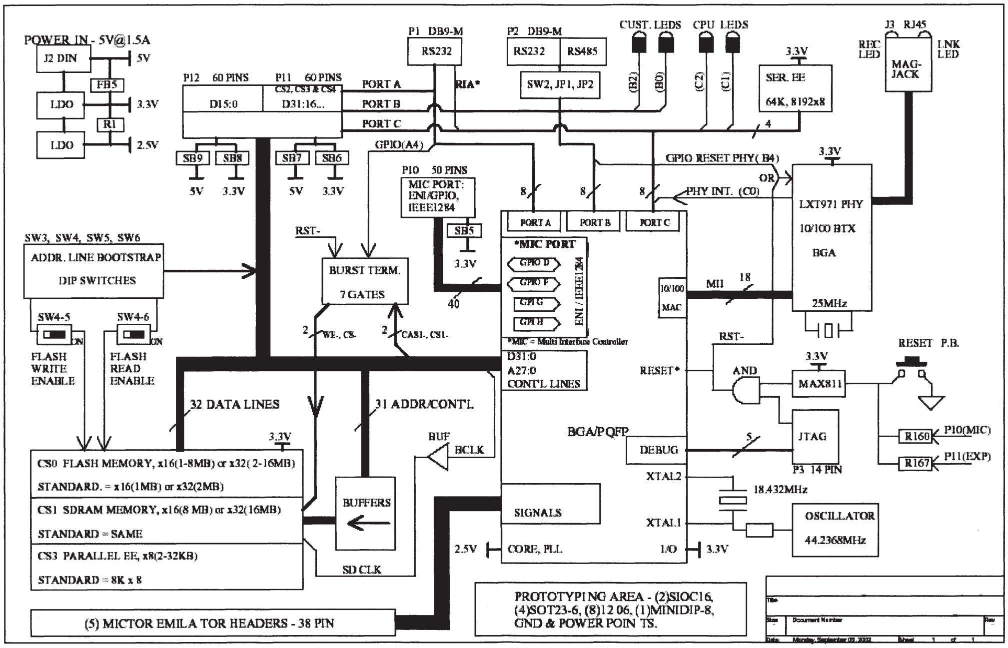


Figure 3-2: Schematic diagram example [3-7]

In the case of schematic diagrams, some of the conventions and rules include:

- A ***title section*** located at the bottom of each schematic page, listing information that includes, but is not limited to, the name of the circuit, the name of the hardware engineer responsible for the design, the date, and a list of revisions made to the design since its conception.
- The use of ***schematic symbols*** indicating the various components of a circuit (see Appendix B).
- Along with the assigned symbol comes a ***label*** that details information about the component (i.e., size, type, power ratings, etc.). Labels for components of a symbol, such as the pin numbers of an IC, signal names associated with wires, and so forth are usually located outside of the schematic symbol.
- ***Abbreviations*** and ***prefixes*** are used for common units of measurement (i.e., k for kilo or 10^3, M for mega or 10^6) and these prefixes replace writing out the units and larger numbers.
- ***Functional groups*** and subgroups of components are typically separated onto different pages.

- ***I/O*** and ***Voltage Source/Ground Terminals***. In general, positive voltage supply terminals are located at the top of the page, and negative supply/ground at the bottom. Input components are usually on the left, and output components are on the right.

Finally, while this book provides an introduction into understanding the various diagrams and recognizing schematic symbols and the devices they represent, it does not replace researching more specifics on the particular diagrams used by your organization, whether through additional reading or purchasing software, or asking the hardware engineers responsible for creating the diagrams what conventions and rules are followed. (For instance, indicating the voltage source and ground terminals on a schematic isn't required, and may not be part of the convention scheme followed by those responsible for creating the schematics. However, a voltage source and a ground are required for any circuit to work, so don't be afraid to ask.) At the very least, the block and schematic diagrams should contain nothing unfamiliar to anyone working on the embedded project, whether they are coding software or prototyping the hardware. This means becoming familiar with everything from where the name of the diagram is located to how the states of the components shown within the diagrams are represented.

One of the most efficient ways of learning how to learn to read and/or create a hardware diagram is via the *Traister* and *Lisk* method[3-10], which involves:

Step 1. Learning the basic symbols that can make up the type of diagram, such as timing or schematic symbols. To aid in the learning of these symbols, rotate between this step and steps 2 and/or 3.

Step 2. Reading as many diagrams as possible, until reading them becomes boring (in that case rotate between this step and steps 1 and/or 3) or comfortable (so there is no longer the need to look up every other symbol while reading).

Step 3. Writing a diagram to practice simulating what has been read, again until it either becomes boring (which means rotating back through steps 1 and/or 2) or comfortable.

3.2 The Embedded Board and the von Neumann Model

In embedded devices, all the electronics hardware resides on a board, also referred to as a printed wiring board (PW) or printed circuit board (PCB). PCBs are often made of thin sheets of fiberglass. The electrical path of the circuit is printed in copper, which carries the electrical signals between the various components connected on the board. All electronic components that make up the circuit are connected to this board, either by soldering, plugging in to a socket, or some other connection mechanism. All of the hardware on an embedded board is located in the hardware layer of the Embedded Systems Model (see Figure 3-3).

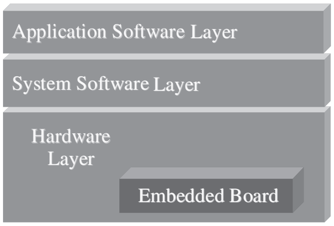


Figure 3-3: Embedded board and the Embedded Systems Model

At the highest level, the major hardware components of most boards can be classified into five major categories:

- Central Processing Unit (CPU) – *the master processor*
- Memory – *where the system's software is stored*
- Input Device(s) – *input slave processors and relative electrical components*
- Output Device(s) – *output slave processors and relative electrical components*
- Data Pathway(s)/Bus(es) – *interconnects the other components, providing a "highway" for data to travel on from one component to another, including any wires, bus bridges, and/or bus controllers*

These five categories are based upon the major elements defined by the von Neumann model (see Figure 3-4), a tool that can be used to understand any electronic device's hardware architecture. The von Neumann model is a result of the published work of John von Neumann in 1945, which defined the requirements of a general-purpose electronic computer. Because embedded systems are a type of computer system, this model can be applied as a means of understanding embedded systems hardware.

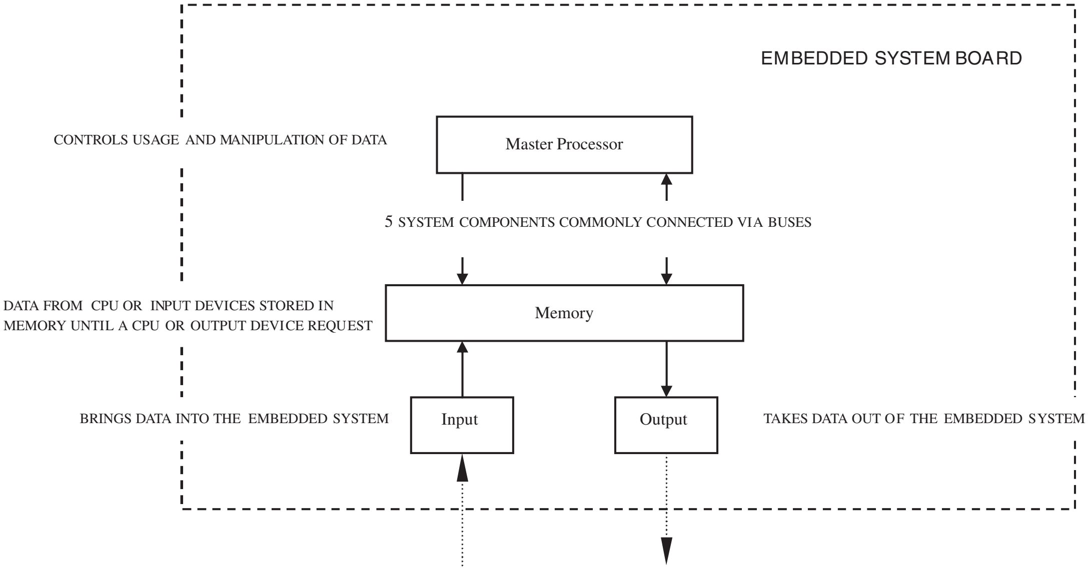
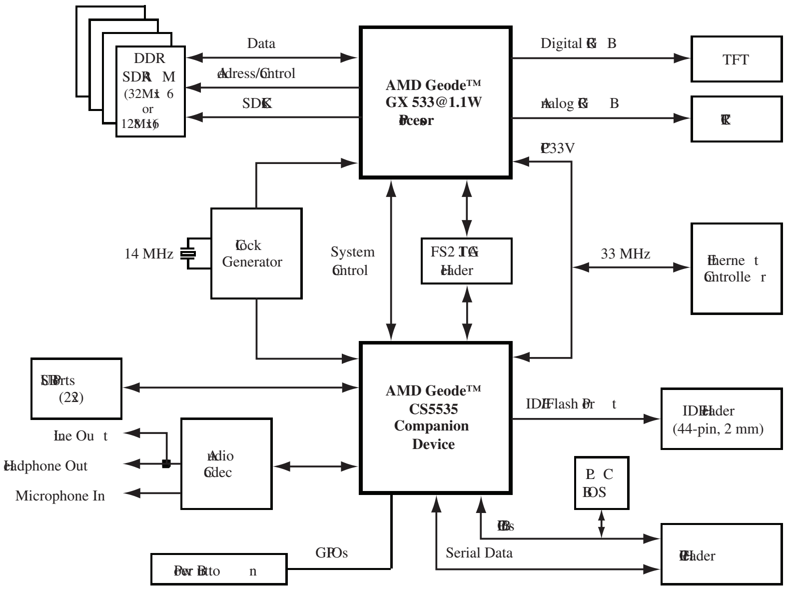


Figure 3-4: Embedded system board organization [3-11]

Based upon the von Neumann architecture model (also referred to as the Princeton architecture).

While board designs can vary widely as demonstrated in the examples of Figures 3-5a, b, c, and d, all of the major elements on these embedded boards—*and on just about any embedded board*—can be classified as either the master CPU(s), memory, input/output, or bus components.



- **Master Processor**: Geode GX533@1.1w (x86)
- **Memory**: ROM (BIOS is located in), SDRAM
- **Input/Output Devices**: CS5535, Audio Codec...
- **Buses**: LPC, PCI

Figure 3-5a: AMD/National Semiconductor x86 reference board [3-1]

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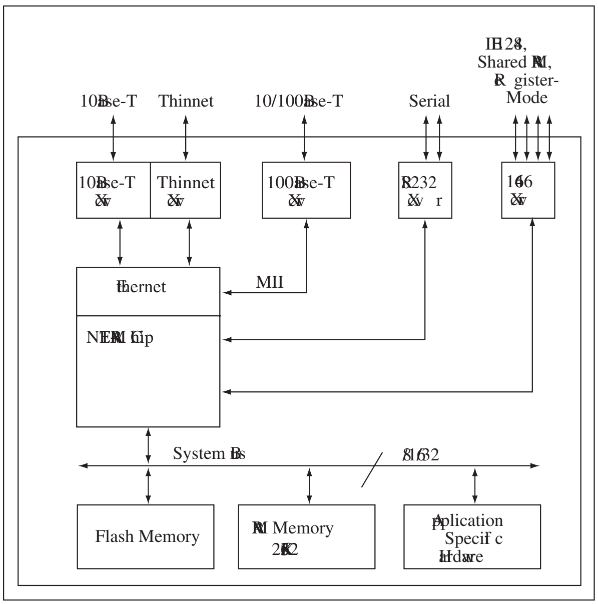
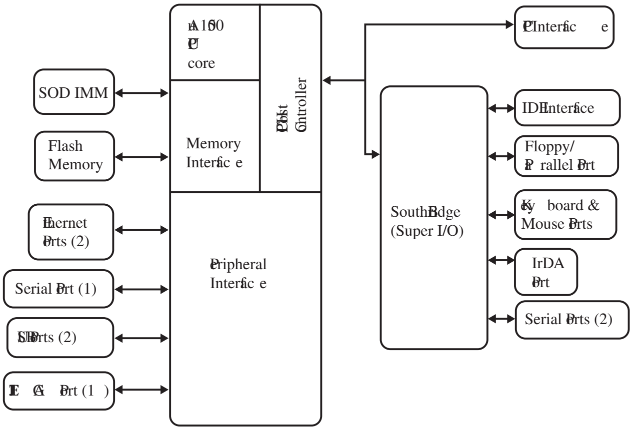


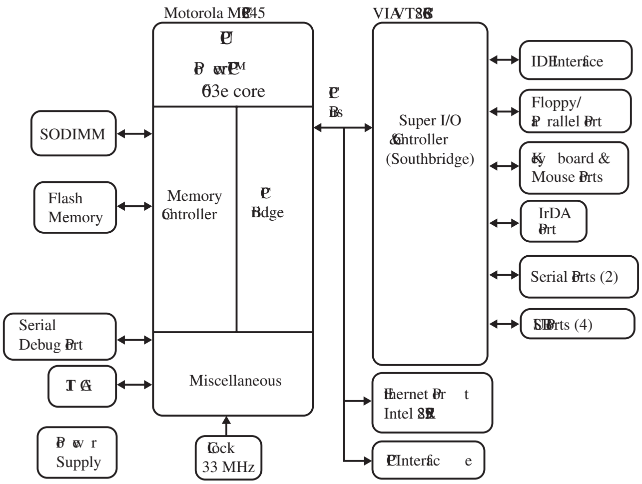
- **Master Processor**: Net+ARM ARM7
- **Memory:** Flash, RAM
- **Input/Output Devices**: 10Base-T transceiver, Thinnet transceiver, 100Base-T transceiver, RS-232 transceiver, 16646 transceiver , …
- **Buses**: System Bus, MII, …

Figure 3-5b: Net Silicon ARM7 reference board [3-2]



- **Master Processor**: Encore M3 (Au1500-based) processor
- **Memory:** Flash, SODIMM
- **Input/Output Devices**: Super I/O,…
- **Buses**: PCI, …

Figure 3-5c: Ampro MIPS reference board [3-3]



- **Master Processor**: MPC8245
- **Memory:** Flash, SODIMM
- **Input/Output Devices**: Super I/O, 82559 Transceiver, …
- **Buses**: PCI, …

Figure 3-5d: Ampro PowerPC reference board [3-4]

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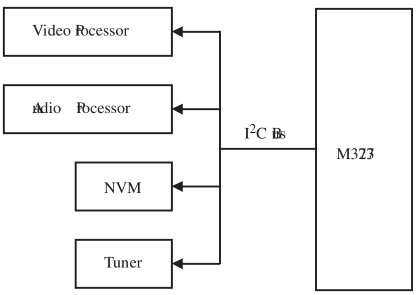


- **Master Processor**: M37273 (8-bit) TV Microcontroller
- **Memory:** NVM
- **Input/Output Devices**: Video processor, Audio Processor, Tuner, …
- **Buses**: I^{2}C, …

Figure 3-5e: Mitsubishi analog TV reference board

In order to understand how the major components on an embedded board function, it is useful to first understand what these components consist of and why. All of the components on an embedded board, including the major components introduced in the von Neumann model, are made up of one or some combination of interconnected **basic electronic devices**, such as wires, resistors, capacitors, inductors, and diodes. These devices also can act to connect the major components of a board together. At the highest level, these devices are typically classified as either ***passive*** or ***active*** components. In short, passive components include devices such as wires, resistors, capacitors and inductors that can only receive or store power. Active components, on the other hand, include devices such as transistors, diodes, and integrated circuits (ICs) that are capable of delivering as well as receiving and storing power. In some cases, active components themselves can be made up of passive components. Within the passive and active families of components, these circuit devices essentially differ according to how they respond to *voltage* and *current*.

3.3 Powering the Hardware

Power is the rate that energy is expended or work is performed. This means that in alternating current (AC) and direct current (DC) circuits, the power associated with each element on the board equals the current through the element multiplied by the voltage across the element ($P = VI$). Accurate power and energy calculations must be done for all elements on an embedded board to determine the power consumption requirements of that particular board. This is because each element can only handle a certain type of power, so AC-DC converters, DC-AC converters, direct AC-AC converters, and so on may be required. Also, each element has a limited amount of power that it requires to function, that it can handle, or that it dissipates. These calculations determine what type of voltage source can be used on a board, and how powerful the voltage source needs to be.

In embedded systems, both AC and DC voltage sources are used, because each current generation technique has its pros and cons. AC is easier to generate in large amounts using generators driven by turbines turned by everything from wind to water. Producing large amounts of DC from electrochemical cells (batteries) is not as practical. Also, because transmitting current over long transmission lines results in a significant loss of energy due to the resistance of the wire, most modern electric company facilities transmit electricity to outlets in AC current since AC can be transformed to lower or higher voltages much more easily than DC. With AC, a device called a *transformer*, located at the service provider, is used to efficiently transmit current over long distances with lower losses. The transformer is a device that transfers electrical energy from one circuit to another, and can make changes to the current and voltage during the transfer. The service provider transmits lower levels of current at a higher voltage rate from the power plant, and then a transformer at the customer site decreases the voltage to the value required. On the flip-side, at very high voltages, wires offer less resistance to DC than AC, thus making DC more efficient to transmit than AC over very long distances.

Some embedded boards integrate or plug into ***power supplies***. Power supplies can be either AC or DC. To use an AC power supply to supply power to components using only DC, an AC-to-DC converter can be used to convert AC to the lower DC voltages required by the various components on an embedded board, which typically require 3.3, 5, or 12 volts.

(Note: Other types of converters, such as DC-to-DC, DC-to-AC, or direct AC-to-AC can be used to handle the required power conversions for devices that have other requirements.)

Other embedded boards or components on a board (such as non-volatile memory, discussed in more detail in Chapter 5) rely on ***batteries*** as voltage sources, which can be more practical for providing power because of their size. Battery-powered boards don't rely on a power plant for energy, and they allow portability of embedded devices that don't need to be plugged into an outlet. Also, because batteries supply DC current, no mechanism is needed to convert AC to DC for components that require DC, as is needed with boards that rely on a power supply and outlet supplying AC. Batteries, however, have a limited life and must be either recharged or replaced.

A Quick Comment on Analog vs. Digital Signals

A digital system processes only digital data, which is data represented by only 0's and 1's. On most boards, two voltages represent "0" and "1", since all data is represented as some combination of 1's and 0's. No voltage (0 volts) is referred to as ground, VSS, or low, and 3, 5, or 12 volts are commonly referred to as VCC, VDD or HIGH. All signals within the system are one of the two voltages, or are transitioning to one of the two voltages. Systems can define "0" as low and "1" as high, or some range of 0–1 volts as LOW, and 4–5 volts as HIGH, for instance. Other signals can base the definition of a "1" or "0" on edges (low-to-high) or (high-to-low).

Because most major components on an embedded board, such as processors, inherently process the 1's and 0's of digital signals, a lot of embedded hardware is digital by nature. However, an embedded system can still process analog signals, which are continuous—that is, not only 1's and 0's but values in between as well. Obviously, a mechanism is needed on the board to convert analog signals to digital signals. An analog signal is digitized by a sampling process, and the resulting digital data can be translated back into a voltage "wave" that mirrors the original analog waveform.

Real-World Advice

Inaccurate Signals: Problems with Noise in Analog and Digital Signals

One of the most serious problems in both the analog and digital signal realm involves noise distorting incoming signals, thus corrupting and affecting the accuracy of data. Noise is generally any unwanted signal alteration from an input source, any part of the input signal generated from something other than a sensor, or even noise generated from the sensor itself. Noise is a common problem with analog signals. Digital signals, on the other hand, are at greater risk if the signals are not generated locally to the embedded processor, so any digital signals coming across a longer transmission medium are the most susceptible to noise problems.

Analog noise can come from a wide variety of sources—radio signals, lightning, power lines, the microprocessor, the analog sensing electronics themselves, etc. The same is true for digital noise, which can come from mechanical contacts used as computer inputs, dirty slip rings that transmit power/data, limits in accuracy/dependability of input source, and so forth.

The key to reducing either analog or digital noise is: 1) to follow basic design guidelines to avoid problems with noise. In the case of analog noise this includes not mixing analog and digital grounds, keeping sensitive electronic elements on the board a sufficient distance from elements switching current, limiting length of wires with low signal levels/high impedance, etc. With digital signals, this means routing signal wires away from noise-inducing high current cables, shielding wires, transmitting signals using correct techniques, etc.; 2) to clearly identify the root cause of the problem, which means exactly what is causing the noise. With point 2), once the root cause of the noise has been identified, a hardware or software fix can be implemented. Techniques for reducing analog noise include filtering out frequencies not needed and averaging the signal inputs, whereas digital noise is commonly addressed via transmitting correction codes/parity bits, and/or adding additional hardware to the board to correct any problems with received data.

—Based on the articles by Jack Ganssle "Minimizing Analog Noise" (May 1997), "Taming Analog Noise" (Nov. 1992) and "Smoothing Digital Inputs" (Oct. 1992) Embedded Systems Programming Magazine

3.4 Basic Hardware Materials: Conductors, Insulators, and Semiconductors

All electronic devices used on a board or that come into contact with an embedded board (such as networking transmission mediums) are made up of materials that are generally classified as conductors, insulators, or semiconductors. These categories differ according to the ability of the materials to conduct an electric current. While conductors, insulators, and semiconductors will all conduct given the right environment, ***conductors*** are materials that have fewer impediments to an electric current (meaning they more easily lose/gain valence electrons), and they (coincidentally) have three or fewer valence electrons (see Figure 3-6).

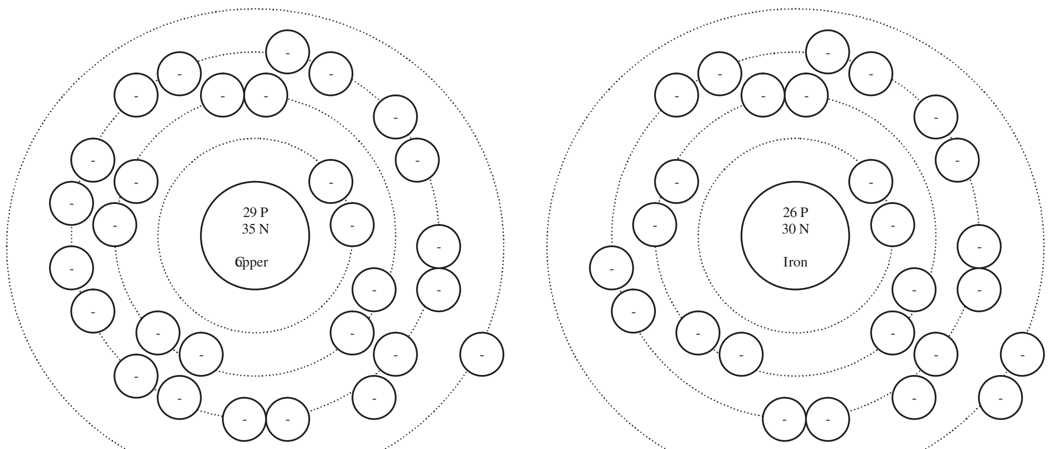


Figure 3-6: Conductors

Most metals are conductors, because most metallic elements have a crystalline makeup that doesn't require a lot of energy to free the valence electrons of their atoms. The atomic lattice (structure) of these metals is composed of atoms that are bound so tightly together that valence electrons aren't closely associated with any individual atom. This means that valence electrons are equally attached to surrounding atoms, and the force attaching them to an individual nucleus is practically nil. Thus, the amount of energy at room temperature to free these electrons is relatively small. Buses and wired transmission mediums are examples of one or more ***wires*** made up of conductive metallic material. *A wire, in a schematic diagram, is typically represented by a straight line: "——" (see Appendix B); in other electronic diagrams (i.e., block) they can also be represented as arrows "←→" .*

Insulators typically have five or more valence electrons (see Figure 3-7), and impede an electric current. This means that they are less likely to lose or gain valence electrons without a great deal of applied energy to the material. For this reason, insulators are typically not the main materials used in buses. Note that some of the best insulators, like conductive metals, are very regular in their crystal lattice and their atoms do tightly bond. The main difference between a conductor and insulator lies in whether the energy of the valence electrons is enough to overcome any barriers between atoms. If this is the case, these electrons are free floating in the lattice. With an insulator, like NaCl for example (sodium chloride, a.k.a. table salt), the valence electrons would have to overcome a tremendous electric field. In short, insulators require greater amounts of energy at room temperature to free their valence electrons in comparison to conductors. Non-metals, such as air, paper, oil, plastic, glass, and rubber, are usually considered insulators.

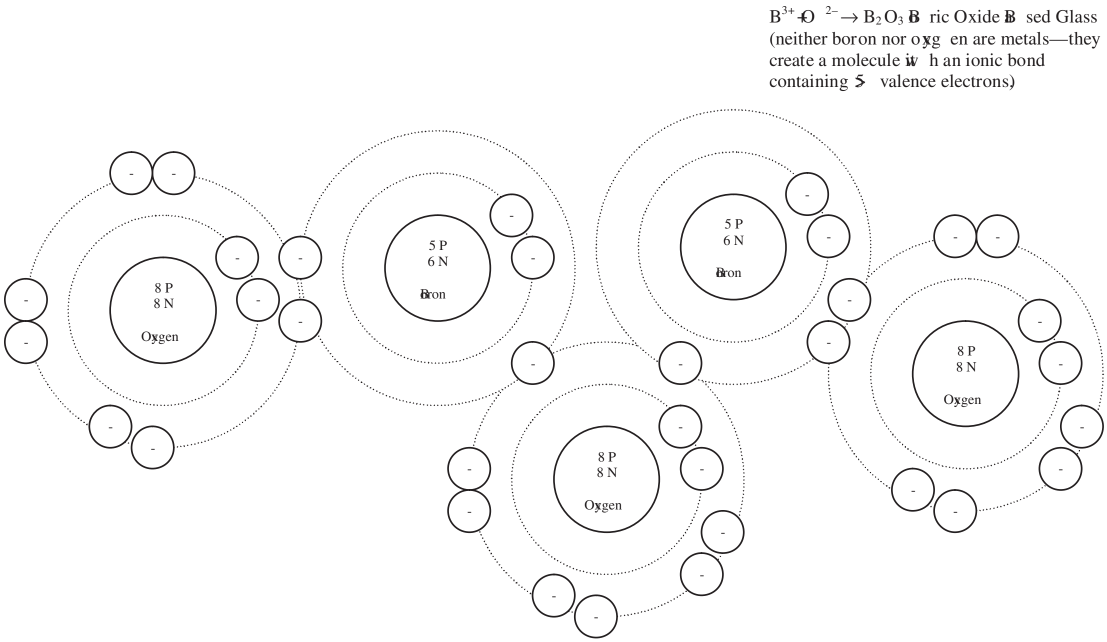


Figure 3-7: Insulators

Air Transmissions via Electromagnetic Waves

The ability of an insulator, air, to transmit data is the basis of wireless communication. Data is transmitted specifically through electromagnetic waves that have the ability to induce a current in a receiving antenna. An antenna is basically a conducting wire that contains a vibrating current that radiates electromagnetic energy into its surroundings. In short, electromagnetic waves are created when an electric charge oscillates at the speed of light, such as within an antenna. The oscillation of an electric charge can be caused by many things—heat, AC circuitry, and so on—but in essence, all elements above the temperature of absolute zero emit some electromagnetic radiation. So, heat (for example) can generate electromagnetic radiation, because the higher the temperature, the faster the electrons oscillate per unit of time, and thus the more electromagnetic energy emitted.

When the electromagnetic wave is emitted, it travels through the empty space, if any, between atoms (of air, of materials, etc.). The electromagnetic radiation is absorbed by that atom, causing its own electrons to vibrate and, after a time, emit a new electromagnetic wave of the same frequency as the wave it absorbed. It is, of course, usually intended at some point for some type of receiver to intercept one of these waves, but the remaining electromagnetic waves will continue to travel indefinitely at the speed of light (though they do weaken the further they travel from their original source—the amplitude/strength of a wave is inversely proportional to the square of the distance). It is for this reason that the different types of wireless mediums (satellite vs. Bluetooth for instance, discussed in Chapter 2) have their limitations in terms of the types of devices and networks they are used in and where their receivers need to be located.

Semiconductors usually have four valence electrons, and are classified as materials whose base elements have a conductive nature that can be altered by introducing other elements into their structure. This means that semiconductive material has the ability to behave both as a conductor and as an insulator. Elements such as silicon and germanium can be modified in such a manner that they have a resistance about halfway between insulators and conductors. The process of turning these base elements into semiconductors starts with the purification of these elements. After purification, these elements have a crystalline structure in which atoms are rigidly locked together in a lattice with the electrons unable to move, making them strong insulators. These materials are then doped to enhance their abilities to conduct electrons. Doping is the process of introducing impurities, which in turn interweaves the silicon or germanium insulator structure with the conductive features of the donor. Certain impurities (like arsenic, phosphorus, antimony, etc.), called donors, create a surplus of electrons creating an N-type semiconductor, while other impurities called acceptors, such as boron, produce a shortage of electrons, creating a P-type semiconductor material (see Figures 3-8a and b).

Note that the fact that semiconductors usually have four valence electrons is a coincidence (silicon and germanium both have four valence electrons, for example). A semiconductor is defined by the energy of the valence electron with respect to the barriers between lattice atoms.

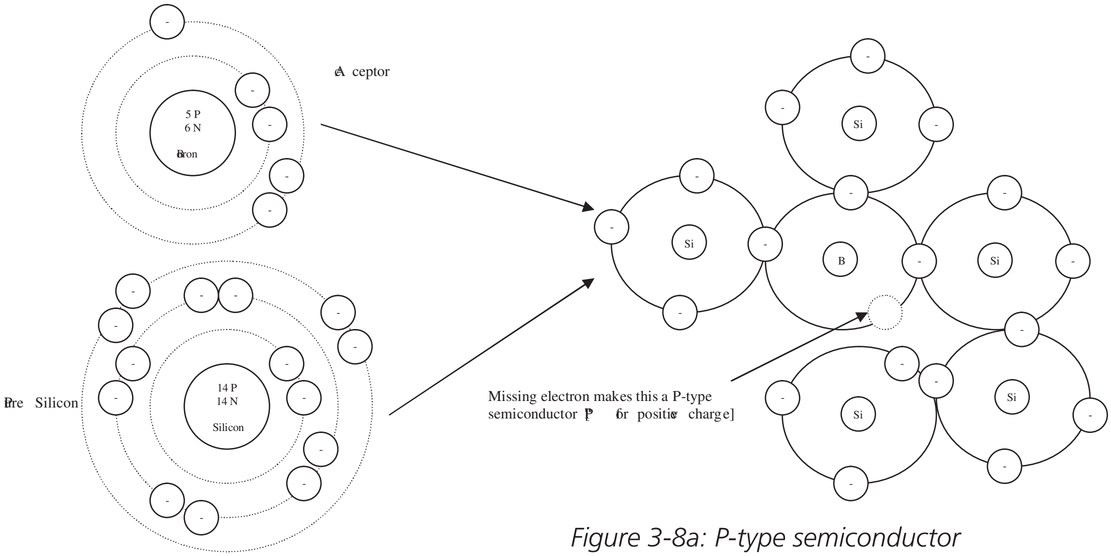


Figure 3-8a: P-type semiconductor

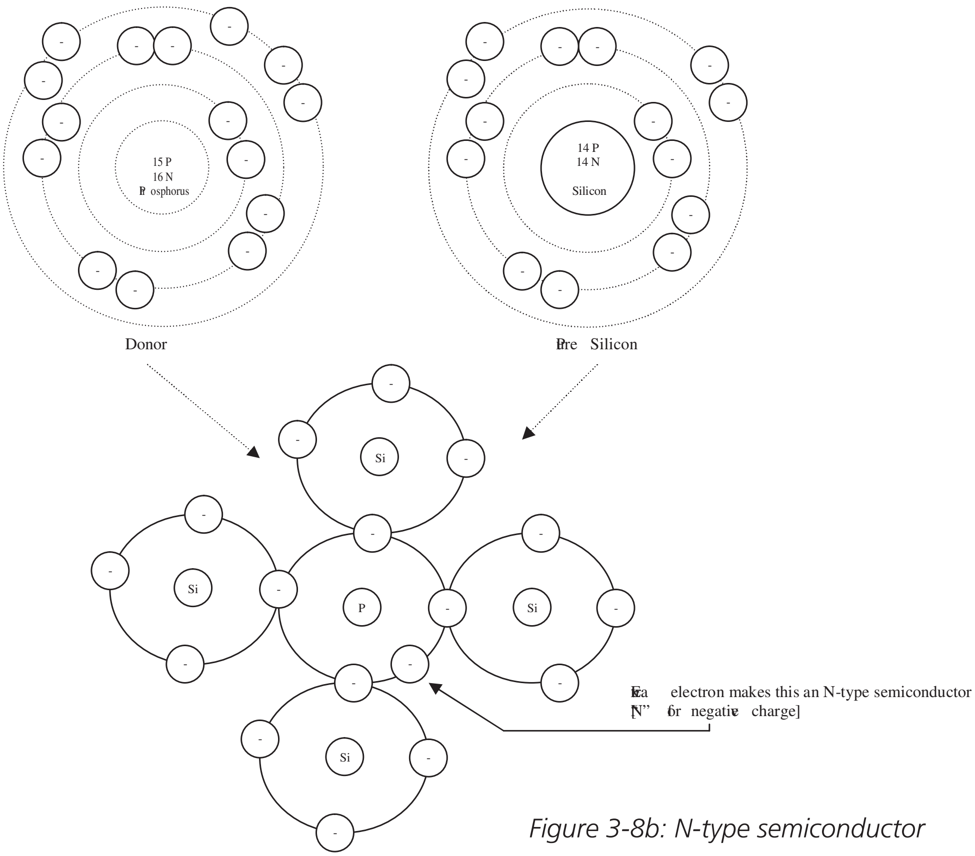


Figure 3-8b: N-type semiconductor

3.5 Common Passive Components on Boards and in Chips: Resistors, Capacitors, and Inductors

Passive electronic components, including wires, can be integrated (along with semiconductive devices, discussed later in this chapter) to form processors and memory chips. These components can also be a part of the circuitry (input circuitry, output circuitry, and so on) found on the board. The next several sub-sections introduce passive components commonly found on an embedded board, mainly the resistor, the capacitor, and the inductor.

3.5.1 The Resistor

Even the best of conductors will offer some resistance to current flow. Resistors are devices made up of conductive materials that have had their conductivity altered in some fashion to allow for an increase in resistance. For example, carbon-composition resistors are created by the mixing of carbon (the conductor) with an insulating material (the impurity). Another technique used in creating resistors is to change the physical shape of the material to alter its resistance, such as winding a wire into a coil, as is the case in wire-wound resistors. There are several different types of resistors in addition to wire-wound and carbon-composition, including current-limiting, carbon film, foil filament wound, fuse and metal film, to name a few. Regardless of type, all resistors provide the same inherent function, to create a resistive force in a circuit. Resistors are a means, within an AC or DC circuit, to control the current or voltage by providing some amount of resistance to the current or voltage that flows across them.

Because resistors, as reflected in Ohm's Law (V = IR), can be used to control current and voltage, they are commonly used in a variety of circuitry both on boards and integrated into processor or memory chips when needed to achieve a particular bias (voltage or current level) for some type of circuitry the resistors are connected to. This means that a set of resistors networked properly to perform a certain function—for example, as attenuators, voltage dividers, fuses, heaters, and so on—provides a specific voltage or current value adjustment that is required for some type of attached circuitry.

Given two resistors with identical resistances, depending on how the resistor was made, a set of properties is considered when selecting between the two for use in a particular circuit. These properties include:

- *Tolerance* in %, which represents at any one time how much more or less precise the resistance of the resistor is at any given time, given its labeled resistance value. The actual value of resistance should not exceed + or – the labeled tolerance. Typically, the more sensitive a particular circuit is to error, the tighter (smaller) the tolerances that are used.

- *Power rating*. When a current encounters resistance, heat, along with some other forms of energy at times, such as light, is generated. The power rating indicates how much power a resistor can safely dissipate. Using a low-powered resistor in a higher-powered circuit can cause a melt-down of that resistor, as it is not able to release the generated heat from the current it carries as effectively as a higher-powered resistor can.
- *Reliability level rating* in %, meaning how much change in resistance might occur in the resistor for every 1000 hours of resistor use.
- *Temperature coefficient of resistance,* or *TCR*. The resistivity of materials that make up the resistor can vary with changes in temperature. The value representing a change in resistance relative to changes in temperature is referred to as the ***temperature coefficient***. If a resistor's resistivity doesn't change in response to a temperature change, it has a "0" temperature coefficient. If a resistor's resistivity increases when the temperature increases and decreases when the temperature decreases, then that resistor has a "positive" temperature coefficient. If a resistor's resistivity decreases when the temperature increases, and increases when the temperature decreases, then that resistor has a "negative" temperature coefficient. For example, conductors typically have a "positive" temperature coefficient, and are usually most conductive (have the least resistance) at room temperature, while insulators typically have fewer freed valence electrons at room temperature. Thus, resistors made up of particular materials that display some characteristic at "room temperature," and a measurably different one at warmer or cooler temperatures, impact what types of systems they ultimately may be used in (mobile embedded devices vs. indoor embedded devices, for example).

While there are many different ways to make resistors, each with their own properties, at the highest level there are only two types of resistors: fixed and variable. ***Fixed resistors*** are resistors that are manufactured to have only one resistance value. Fixed resistors come in many different types and sizes depending on how they are made (see Figure 3-9a), though in spite of the differences in physical appearances, the schematic symbol representing fixed resistors remains the same depending on the schematic standard supported (Figure 3-9b).

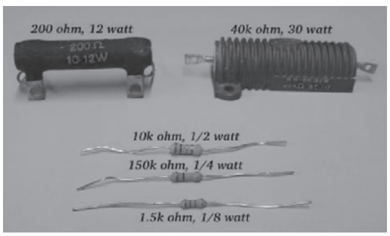


Figure 3-9a: Fixed resistors

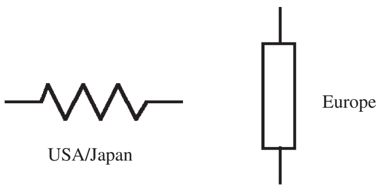


Figure 3-9b: Fixed resistor schematic symbols

For fixed resistors with bodies that are too small to contain their printed property values, the values are calculated from color coded bands located physically on the resistor's body. These color coded bands appear as either vertical stripes, used on fixed resistors with axial leads as shown in Figure 3-10a, or in various locations on the body, used on fixed resistors with radial leads as shown in Figure 3-10b.

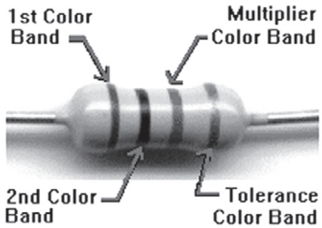


Figure 3-10a:
Fixed resistors with axial leads

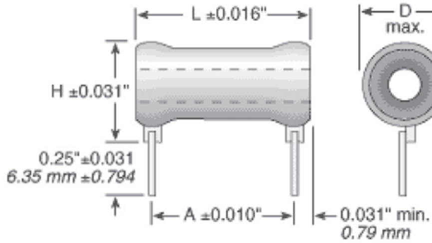


Figure 3-10b:
Fixed resistors with radial leads

A resistor may also include additional color coded bands representing its various properties, such as reliability level ratings, temperature coefficient, tolerance, and so on. While different types of fixed resistors have different numbers and types of bands, the color definitions are typically the same. Tables 3-2a, b, c, and d show the various types of bands that can be found on the body of a fixed resistor along with their meanings.

Color of Band	Digits	Multiplier
Black	0	×1
Brown	1	×10
Red	2	×100
Orange	3	×1K
Yellow	4	×10K
Green	5	×100K
Blue	6	×1M
Purple	7	×10M
Grey	8	×100M
White	9	×1000M
Silver	-	×0.01
Gold	-	×0.1

Table 3-2a: Resistor color code digits and multiplier table [3-6]

Color of Band	Temperature coefficient
Brown	100 ppm
Red	50 ppm
Orange	15 ppm
Yellow	25 ppm

Table 3-2b: Temperature coefficient [3-6]

Color of Band	Reliability Level (%)
Brown	1%
Red	0.1%
Orange	0.01%
Yellow	0.001%

Table 3-2c:
Reliability level (%1000 HR) [3-6]

Color of Band	Tolerance (%)
Silver	± 10%
Gold	± 5%
Brown	± 1%
Red	± 2%
Green	± 0.5%
Blue	± 0.25%
Purple	± 0.1%

Table 3-2d: Tolerance [3-6]

To understand how the color coding works, let's take an example of a 5-band carbon composition resistor with axial leads, in which the bands are arranged as vertical stripes on the resistor's body, with associated colors bands as shown in Figure 3-11. Bands 1 and 2 are digits, band 3 is the multiplier, band 4 is tolerance, and band 5 is reliability. Note that resistors can vary widely in the number and meanings of the bands, and that this is one specific example in which we're given the information and are told how to use the tables to determine resistance and other various properties. This resistor's first three bands are red = 2, green = 5, and brown = ×10. Thus, this resistor has a resistance of 250 Ω (2 and 5 of the red and green bands are the first and second digits, the third brown band "×10" value is the multiplier which is used to multiply "25" by 10, resulting in the value of 250). Taking into account the resistor's tolerance reflected by the red band or ± 2%, this resistor has a resistance value of 250 Ω ± 2%. The fifth band in this example is a yellow band, reflecting a reliability of 0.001%. This means that the resistance of this resistor might change by 0.001% from the labeled value (250 Ω ± 2% in this case) for every 1000 hours of use. *Note: The amount of resistance provided by a resistor is measured in ohms (Ω).*

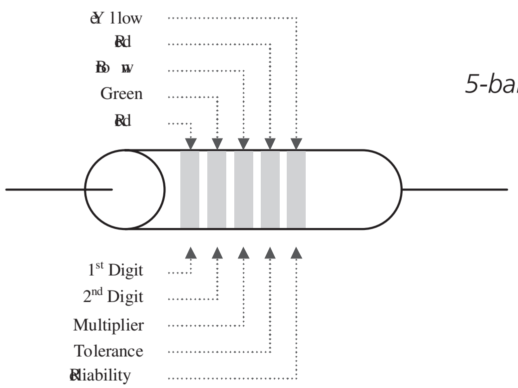


Figure 3-11:
5-band fixed resistor with axial leads example

Variable resistors vary their resistance on-the-fly, as opposed to manufactured fixed resistors. Resistance can be varied manually (potentiometers), by changes in light (photosensitive/photo resistor), by changes in temperature (thermally sensitive/termistor), and so on. Figures 3-12a and b show what some variable resistors physically look like, as well as how they are symbolized in schematics.

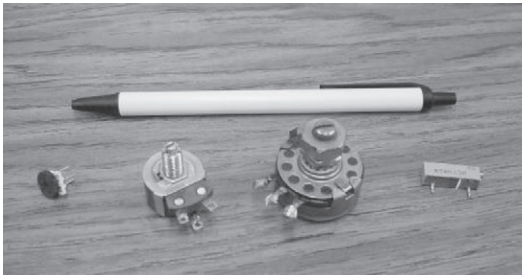


Figure 3-12a: Variable resistor's appearance

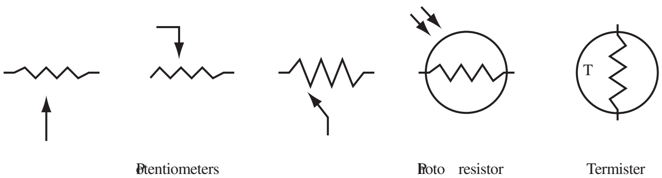


Figure 3-12b: Variable resistor's schematic symbols

3.5.2 The Capacitor

Capacitors are made up of conductors typically in the form of two parallel metal plates separated by an insulator, which is a dielectric such as air, ceramic, polyester, mica, and so forth, as shown in Figure 3-13a.

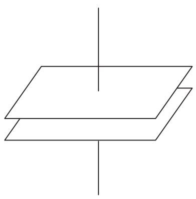


Figure 3-13a: Capacitor

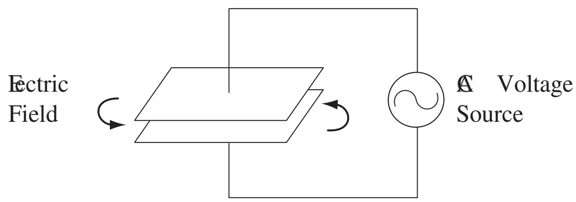


Figure 3-13b: Capacitor in circuit

When each of the plates is connected to an AC voltage source (see Figure 3-13b), the plates accumulate opposing charges, positive in one plate and negative in the other. Electrons are surrounded by electric fields produced by that charge. An electric field emanates outwardly and downwardly from the source, in this case the charged plate, diminishing in field strength as it gets further from the source. The electric field created between the two plates acts to temporarily store the energy and keep the plates from discharging. If a wire were to connect the two plates, current would flow until both plates were no longer charged—or as is the case with AC voltage sources, when the polarity changes, the plates then discharge.

In short, capacitors store energy in electric fields. Like the resistor, they impede the flow of energy, but unlike the resistor, which dissipates some of this energy intentionally and is typically used in both AC and DC circuits, the capacitor is more commonly used in AC circuits, and gives this same energy back to the circuit in its original form (electrically) when the plates are discharged. Note that, depending on how the capacitor is made, manufacturing imperfections may result in a capacitor not functioning perfectly, causing some unintentional loss of energy in the form of heat.

> Any two conductors located in close proximity can act as capacitors (with air being the dielectric). This phenomena is called inter-electrode capacitance. It is for this reason that in some devices (involving radio frequencies) this phenomena is minimized by enclosing some electronic components.

A set of properties is considered when selecting capacitors for use in a particular circuit, namely:

- *Temperature coefficient of capacitance*. Similar in meaning to TCR (temperature coefficient of resistance). If a capacitor's conductance doesn't change in response to a temperature change, it has a "0" temperature coefficient. If a capacitor's capacitance increases when the temperature increases, and decreases when the temperature decreases, then that capacitor has a "positive" temperature coefficient. If a capacitor's capacitance decreases when the temperature increases, and increases when the temperature decreases, then that capacitor has a "negative" temperature coefficient.
- *Tolerance* in %, which represents at any one time how much more or less precise the capacitance of a capacitor is at any given time given its labeled capacitance value (the actual value of capacitance should not exceed + or – the labeled tolerance).

As with resistors, capacitors can be integrated into a chip, and depending on the capacitor, used in everything from DC power supplies to radio receivers and transmitters. Many different types of capacitors exist (variable, ceramic, electrolytic, epoxy, and so on), differing by the material of the plates and dielectric and, like resistors, by whether they can be adjusted on-the-fly (see Figures 3-14a and b).

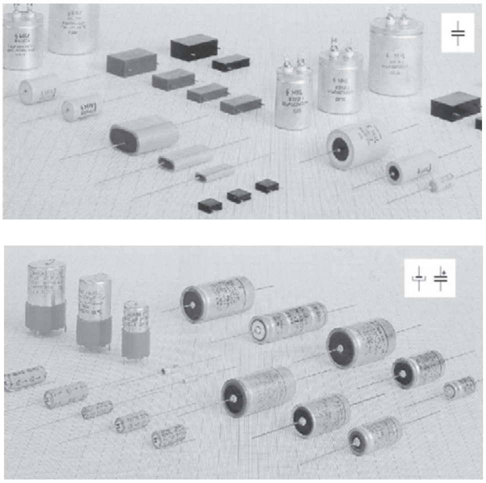


Figure 3-14a: Capacitors

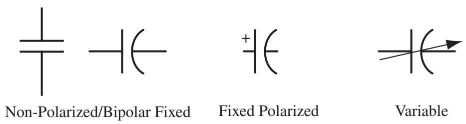


Figure 3-14b: Capacitor's schematic symbols

3.5.3 Inductors

Inductors, like capacitors, store electrical energy in AC circuits. With capacitors, however, energy is temporarily stored in an electric field, whereas inductors temporarily store energy in a *magnetic field*. These magnetic fields are produced by the movement of electrons, and can be visualized as rings surrounding an electric current (see Figure 3-15a). The direction of electron flow determines the direction of the magnetic field (see Figure 3-15b).

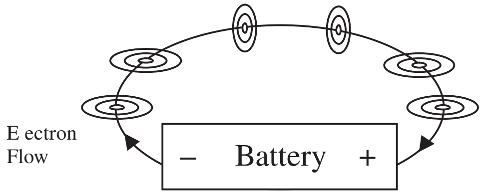


Figure 3-15a: Magnetic fields

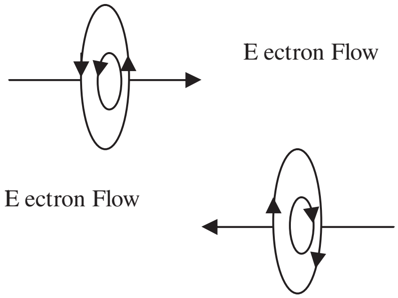


Figure 3-15b: Direction of magnetic fields

All materials, even conductors, have some resistance and thus give off some energy. Some of this energy is stored within the magnetic fields surrounding the wire. Inductance is the storage of energy within the magnetic field surrounding a wire with a current flowing through it (and like capacitance, can occur unintentionally). When a change occurs in the current stream, as happens in an AC circuit, the magnetic field changes and thus “induces a force on a charged object” (Faraday’s Law of Induction). Any expansion, due to a current increase, means an increase in the energy stored by the inductor, whereas a collapse of a magnetic field, due to a lack of current, will release that energy back into the circuit. Changes in current are reflected in how inductance is measured. Measured in units of henries (H), inductance is the ratio between the rate of current change and the voltage across the inductor.

As mentioned, all wires with some current have some sort of inductance, however minimal. Because magnetic flux is much higher for a coiled wire than for a straighter wire, most common inductors are made up of a coiled wire, although, again, inductors can be made up of a single wire or set of wires. Adding some type of core other than air, such as ferrite or powdered iron within the coiled-up wire increases the magnetic flux density many times over. Figures 3-16a and b show some common inductors and their schematic symbol counterparts.

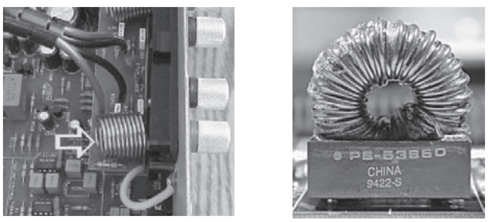


Figure 3-16a:
Inductor’s appearance

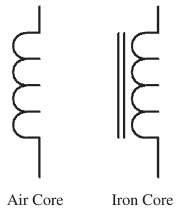


Figure 3-16b:
Inductor’s schematic symbols

The properties that define inductance include the number of individual coils (the more coils, the larger the inductance), the diameter of the coils (which is directly proportional to inductance), the overall shape of the coil (cylindrical/solenoidal, doughnut-shaped/toroidal, and so on), and the overall length of the coiled wire (the longer it is, the smaller the inductance).

3.6 Semiconductors and the Active Building Blocks of Processors and Memory

While P-type and N-type semiconductors are the basic types of semiconductors, as discussed in Section 3.4, they are not usually very useful on their own. These two types must be combined in order to be able to do anything practical. When P-type and N-type semiconductors are combined, the contact point, called the ***P-N Junction***, acts as a one-way gate to allow electrons to flow within the device in a direction dependent on the polarity of the materials. P and N-type semiconductive materials form some of the most common basic electronic devices that act as the main building blocks in processor and memory chips: diodes and transistors.

3.6.1 Diodes

A diode is a semiconductor device made up of two materials, one P-type and one N-type, joined together. A terminal is connected to each of the materials, called an ***anode***, labeled “A” in the schematic symbol in Figure 3-17b, and a ***cathode***, labeled “C” in the schematic in Figure 3-17b.

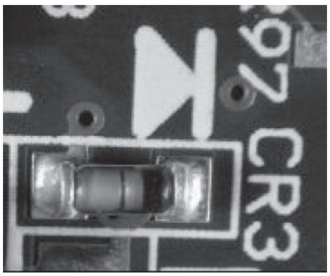


Figure 3-17a: Diode and light emitting diode (LED)

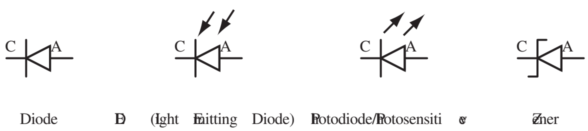


Figure 3-17b: Diode schematic symbols

These materials work together to allow current to flow in only one direction. Current flows through a diode from the anode to cathode as long as the anode has a higher (positive) voltage; this phenomena is called forward biasing. Current flows in this condition because the electrons flowing from the voltage source are attracted to the P-type material of the diode through the N-type material (see Figure 3-18a).

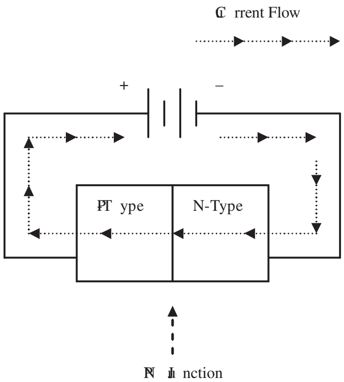


Figure 3-18a:
Diode in forward bias

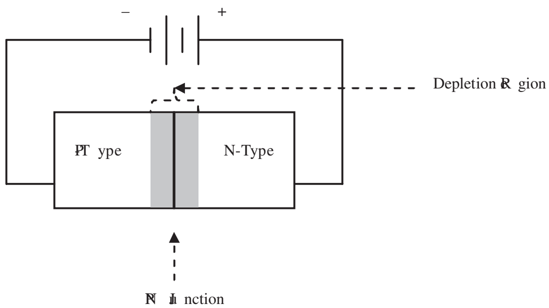


Figure 3-18b:
Diode in reverse bias

When current will not flow through the diode because the cathode has a higher (positive) voltage than the anode, the diode acts like a variable capacitor, whose capacitance changes depending on the amount of reverse voltage. This is called reverse biasing. In this case (as shown in Figure 3-18b), the electrons are pulled away from the P-type material in the diode, creating a ***depletion region***, a section surrounding the P-N junction that has no charge and acts as an insulator, resisting current flow.

There are several different types of diodes, each with their own common uses, such as rectifier diodes that convert AC to DC by keeping the polarity constant, PIN diodes as switches, zener diodes for voltage regulation, and so on. Some of the most recognizable diodes on a board are the ***Light Emitting Diodes*** or ***LEDs***, shown in Figure 3-19. LEDs are the blinking or steady lights that can indicate anything from PowerON, to problems with the system, to remote-control signals, depending on how they are designed. LEDs are designed to emit visible or infrared (IR) light when forward biased in a circuit.

As a final note, keep in mind that higher forms of semiconductor logic are based upon the diode depletion effect. This effect generates a region where the barrier is higher than the average valence electron energy, and the barrier can be influenced by voltage.

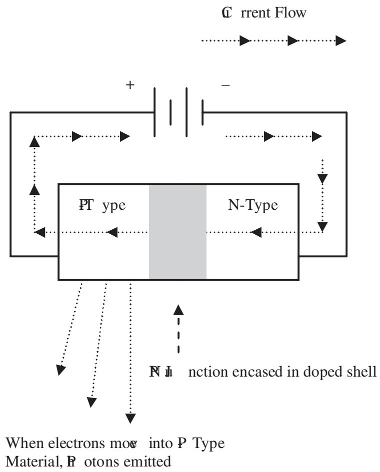


Figure 3-19:
LED in forward bias

3.6.2 Transistors

"Transistor" is the contraction for *current-**tran**sferring re**sistor***.[3-5] Transistors are made up of some combination of P-type and N-type semiconductor material, with three terminals connecting to each of the three materials (see Figure 3-20a). It is the combination and versatility of these materials that, depending on the type of transistor, allow them to be used for a variety of purposes, such as current amplifiers (amplification), in oscillators (oscillation), in high-speed integrated circuits (ICs, to be discussed later this chapter), and/or in switching circuits (DIP switches, push buttons, and so on commonly found on off-the-shelf reference boards for example). While there are several different types of transistors, the two main types are the ***bipolar junction transistor*** (BJT) and the ***field effect transistor*** (FET).

The BJT, also referred to as the bipolar transistor, is made up of three alternating types of P-type and N-type material, and are subclassed based on the combination of these materials. There are two main subclasses of bipolar transistors, PNP and NPN. As implied by their names, a PNP BJT is made up of two sections of P-type materials, separated by a thin section of N-type material, whereas the NPN bipolar transistor is made up of two sections of N-type material, separated by a thin section of P-type material. As shown in Figures 3-20a and b, each of these sections has an associated terminal (electrode): an *emitter*, *base*, and a *collector*.

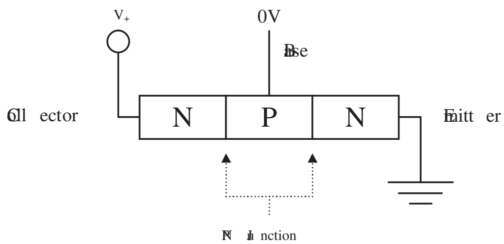


Figure 3-20a: NPN BJT "OFF"

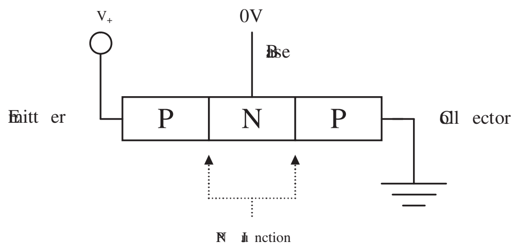
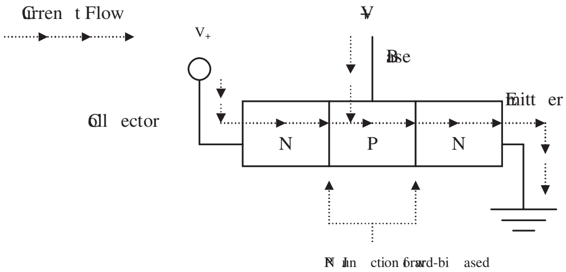


Figure 3-20b: PNP BJT "OFF"

When the NPN BJT is OFF (as shown in Figure 3-20a), electrons in the emitter cannot bypass the P-N junction to flow to the collector, because there is no biasing voltage (0 volts) at the base to pressure electrons over the junctions.



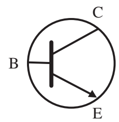
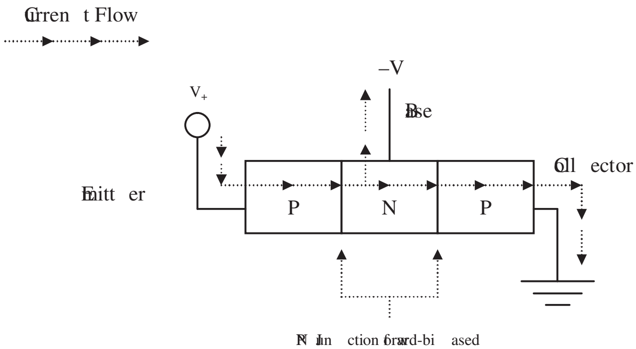


Figure 3-21a: NPN BJT “ON”

Figure 3-21b: NPN BJT schematic symbol

To turn the NPN BJT “ON” (as shown in Figure 3-21a), a positive voltage and input current must be applied at the base so escaping electrons from the emitter are attracted to the P-type base, and, because of the thinness of the P-type material, these electrons then flow to the collector. This then creates a (positive) current flow from the collector to the emitter. This current flow is a combination of the base current and collector current, and so, the larger the base voltage, the greater the emitter current flow. Figure 3-21b shows the NPN BJT schematic symbol, which includes an arrow indicating the direction of output current flow ***from*** the emitter when the transistor is ON.

When the PNP BJT is OFF (as shown in Figure 3-20b), electrons in the collector cannot bypass the PN junction to flow to the emitter, because the 0 volts at the base is placing just enough pressure to keep electrons from flowing. To turn the PNP BJT ON (as shown in Figure 3-22a), a negative base voltage is used to decrease pressure and allow a positive current flow out of the collector, with a small output current flowing out of the base, as well. Figure 3-22b shows the PNP BJT schematic symbol, which includes an arrow indicating the direction of current flow ***into*** the emitter and out the collector terminal when the transistor is ON.



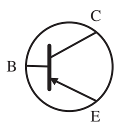


Figure 3-22a: PNP BJT “ON”

Figure 3-22b: PNP BJT schematic symbol

In short, PNP and NPN BJTs work in the same manner, given the opposite directions of current flow, the P and N type material makeup, and the voltage polarities applied at the base.

Like the BJT, the FET is made up of some combination of P-type and N-type semiconductor material. Like the BJT, FETs have three terminals, but in FETs these terminals are called a *source*, a *drain/sink*, and a *gate* (see Figure 3-22). In order to function, FETs do not require a biasing current, and are controlled via voltage alone. Beyond this, there are several subtypes of FETs that function and are designed differently, the most common falling under the families of the ***metal-oxide-semiconductor field-effect transistor*** (MOSFET) and the ***junction field-effect transistor*** (JFET).

There are several types of MOSFETs, the main two subclasses of which are ***enhancement*** MOSFETs and ***depletion*** MOSFETs. Like BJTs, enhancement-type MOSFETs become less resistant to current flow when voltage is applied to the gate. Depletion-type MOSFETs have the opposite reaction to voltage applied to the gate: they become more resistant to current flow. These MOSFET subclasses can then be further divided according to whether they are P-channel or N-channel transistors (see Figure 3-23a, b, c, and d).

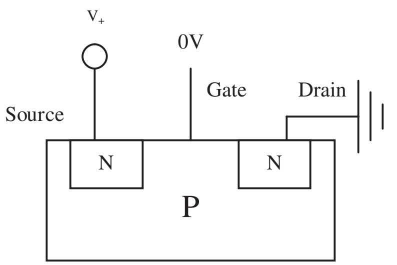


Figure 3-23a:
N-channel enhancement MOSFET "OFF"

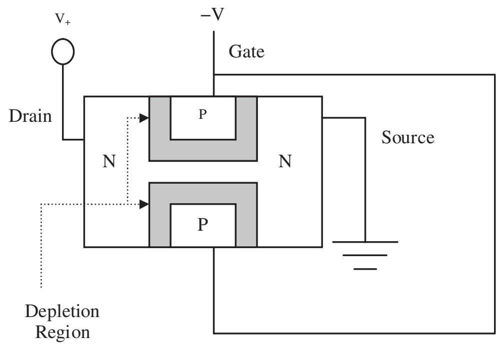


Figure 3-23b:
N-channel depletion MOSFET "OFF"

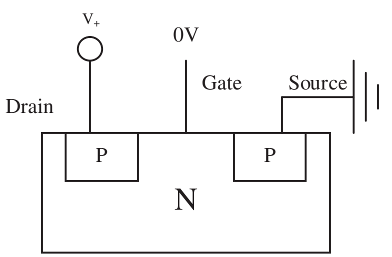


Figure 3-23c:
P-channel enhancement MOSFET "OFF"

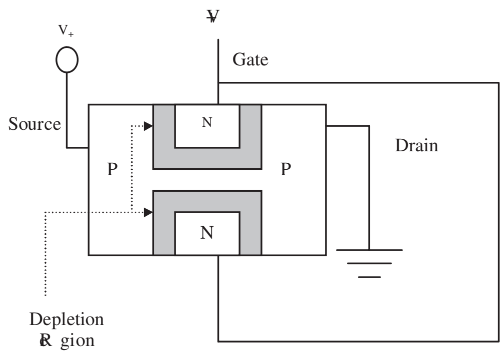


Figure 3-23d:
P-channel depletion MOSFET "OFF"

In N-channel enhancement MOSFETs, the source and drains are N-type (– charge) semiconductor material and sit on top of P-type material (+ charge). In P-channel enhancement MOSFETs, the source and drains are P-type (+ charge) semiconductor material and sit on top of N-type material (– charge).When no voltage is applied to the gate, these transistors are in the OFF state (see Figure 3-23a and c), because there is no way for current to flow from the source to the drain (for N-channel enhancement MOSFETs) or from drain to source for P-channel enhancement MOSFETs.

N-channel depletion MOSFETs are in the "OFF" state when a negative voltage is applied to the gate (as shown in Figure 3-23b) to create a *depletion region*, an area in which no current can flow, making it more difficult for electrons to flow through the transistor because of a smaller available channel for current to flow through. The more negative the voltage applied to the gate, the larger the depletion region, and the smaller the channel available for electron flow. As seen in Figure 3-23d, the same holds true for a P-channel depletion MOSFET, except because of the reversed type (polarity) of materials, the voltage applied at the gate to turn the transistor OFF is positive instead of negative.

The N-channel enhancement MOSFET is in the ON state when "+" (positive) voltage is applied to the gate of the transistor. This is because electrons in the P-type material are attracted to the area under the gate when the voltage is applied, creating an electron channel between the drain and source. So, with the positive voltage on the other side of the drain, a current flows from the drain (and gate) to the source over this electron channel. P-channel enhancement MOSFETs, on the other hand, are in the ON state when "–" (negative) voltage is applied to the gate of the transistor. This is because electrons from the negative voltage source are attracted to the area under the gate when the voltage is applied, creating an electron channel between the source and drain. So, with the positive voltage on the other side of the source, current flows from the source to the drain (and gate) over this electron channel (see Figures 3-24a and c).

Because depletion MOSFETs are inherently conductive, when there is no voltage applied to the gates of an N-channel or P-channel depletion MOSFET, there is a wider channel in which electrons are free to flow through the transistor from, in the case of an N-channel depletion MOSFET, the source to the drain and, in the case of the P-channel depletion MOSFET, the drain to the source. In these cases, the MOSFET depletion transistors are in the "ON" state (see Figures 3-24b and d).

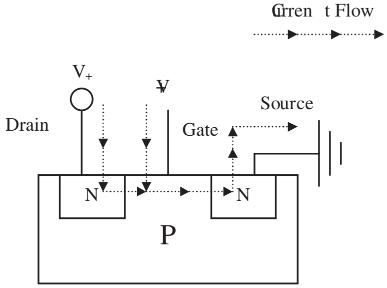


Figure 3-24a:
N-channel enhancement MOSFET "ON"

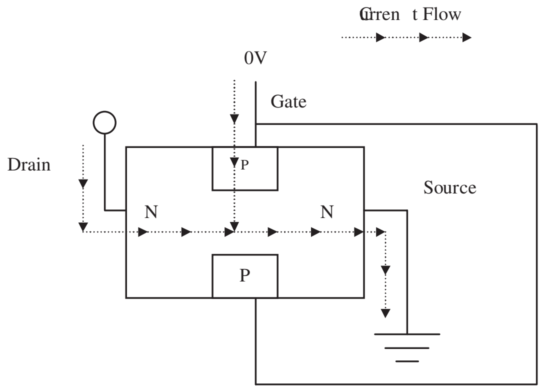


Figure 3-24b:
N-channel depletion MOSFET "ON"

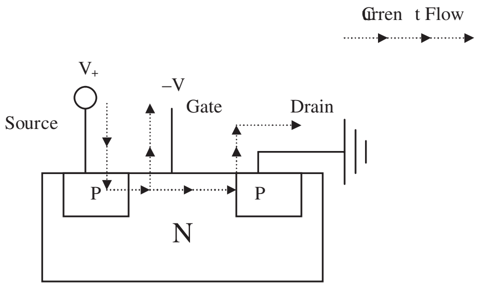


Figure 3-24c:
P-channel enhancement MOSFET "ON"

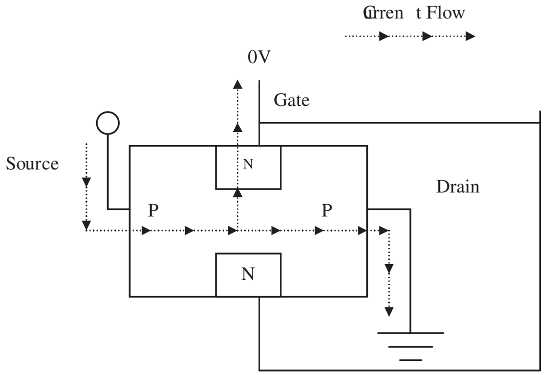


Figure 3-24d:
P-channel depletion MOSFET "ON"

As seen in Figure 3-25, the schematic symbols for the MOSFET enhancement and depletion N-channel and P-channel transistors contain an arrow that indicates the direction of current flow for N-channel MOSFET depletion and enhancement transistors (into the gate, and with what is coming into the drain, output to the source), and P-channel MOSFET depletion and enhancement transistors (into the source, and out of the gate and drain) when these transistors are ON.

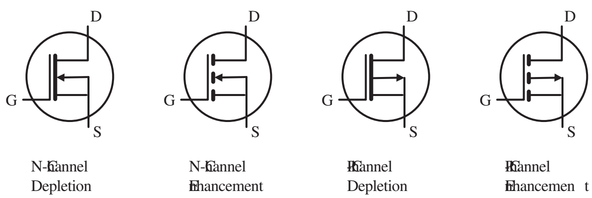


Figure 3-25: MOSFET schematic symbols

The JFET transistors are subclassed as either N-channel or P-channel JFETs, and like depletion-type MOSFETs, become more resistive to current flow when voltage is applied to their gates. As shown in Figure 3-26a, an N-channel JFET is made up of the drain and source connecting to N-type material, with the gate connecting to two P-type sections on either side of the N-type material. A P-channel JFET has the opposite configuration, with the drain and source connecting to P-type material, and the gate connecting to two N-type sections on either side of the P-type material (see Figure 3-26b).

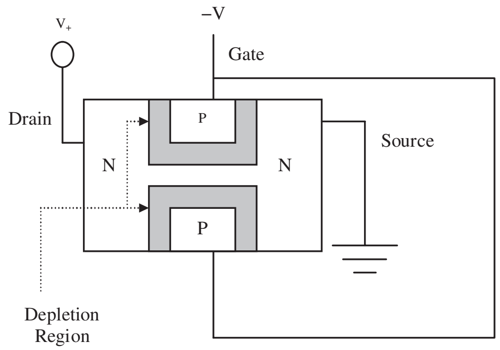


Figure 3-26a: N-channel JFET "OFF"

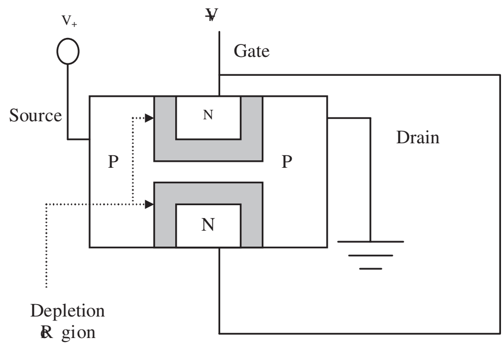


Figure 3-26b: P-channel JFET "OFF"

In order to turn the N-channel JFET transistor "OFF", a negative voltage must be applied to the gate (as shown in Figure 3-26a) to create a depletion region, an area in which no current can flow, making it more difficult for electrons to flow through the transistor because of a smaller available channel for current to flow through. The more negative the voltage applied to the gate, the larger the depletion region, and the smaller the channel available for electron flow. As seen in Figure 3-26b, the same holds true for a P-channel JFET, except because of the reversed type of materials, the voltage applied at the gate to turn the transistor OFF is positive instead of negative.

When there is no voltage applied to the gates of an N-channel or P-channel JFET, there is a wider channel in which electrons are free to flow through the transistor from, in the case of an N-channel JFET, the source to the drain and, in the case of the P-channel JFET, the drain to the source. In this case, the JFET transistors are in the "ON" state (see Figures 3-27a and b).

As seen in Figure 3-28, the schematic symbols for the JFET N-channel and P-channel transistors contain an arrow that indicates the direction of current flow for N-channel (into the gate, and with what is coming into the drain, output to the source) and P-channel (into the source, and out of the gate and drain) when these transistors are ON.

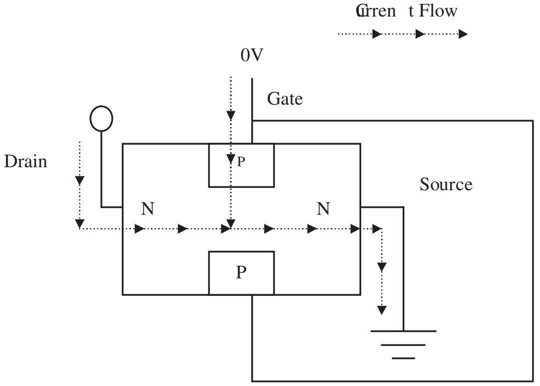


Figure 3-27a: N-channel JFET "ON"

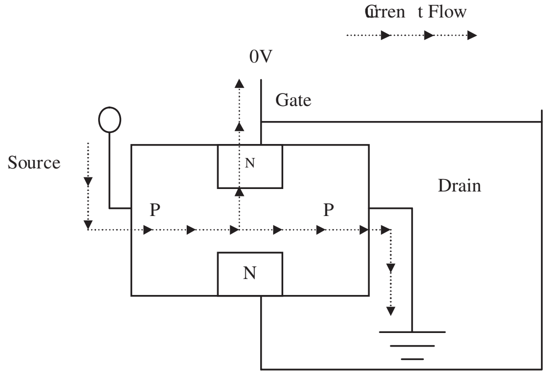


Figure 3-27b: P-channel JFET "ON"

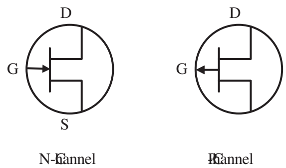


Figure 3-28: JFET N-channel and P-channel schematic symbols

Again, there are other types of transistors (such as unijunction) but essentially the major differences between all transistors include size (FETs can typically be designed to take up less space than BJTs, for instance), price (FETs can be cheaper and simpler to manufacture than BJTs, because they are only controlled via voltage), usage (FETs and unijunctions are typically used as switches, BJTs in amplification circuits), and so on. In short, transistors are some of the most critical elements in the design of more complex circuitry on an embedded board. The next several pages will indicate how they are used.

3.6.3 Building More Complex Circuitry from the Basics: Gates

Transistors that can operate as switches, such as MOSFETs, are operating in one of two positions at any one time: ON (1) or OFF (0). MOSFETs are implemented in a switched electronic circuit in which the switch (the transistor) controls the flow of electrons over the wire by (if an nMOS) being ON (completing the circuit path) or OFF (breaking the circuit path), or vice-versa if a pMOS. It is because embedded hardware communicates via various combinations of bits (0's and 1's) that transistors like the MOSFET are used in circuits that can store or process bits, since these types of transistors can function as a switch that is either a value of "0" or "1". In fact, transistors, along with other electronic components such as diodes and resistors are the main "building blocks" of more complex types of electronic switching circuits, called logical circuits or ***gates***. Gates are designed to perform *logical* binary operations, such as AND, OR, NOT, NOR, NAND, XOR, and so on. Being able to create logic circuits is important, because these operations are the basis of all mathematical and logical functions used by the programmer and processed by the hardware. Reflecting logical operations, gates are designed to have one or more input(s) and one output, supporting the requirements to perform logical binary operations. Figures 3-29a and b outline some examples of the truth tables of some logical binary operations, as well as one of the many possible ways transistors (MOSFETs are again used here as an example) can build such gates.

AND

I1	I2	O
0	0	0
0	1	0
1	0	0
1	1	1

OR

I1	I2	O
0	0	0
0	1	1
1	0	1
1	1	1

NOT

I1	O
0	1
1	0

NAND

I1	I2	O
0	0	1
0	1	1
1	0	1
1	1	0

NOR

I1	I2	O
0	0	1
0	1	0
1	0	0
1	1	0

XOR

I1	I2	O
0	0	0
0	1	1
1	0	1
1	1	0

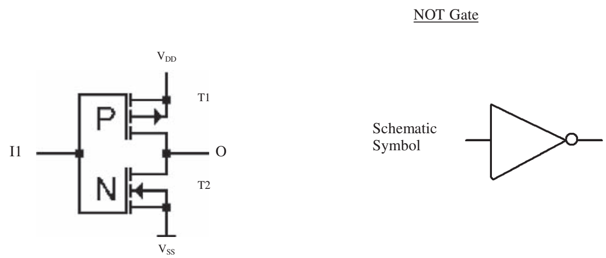
…

Figure 3-29a: Truth tables of logical binary operations

Figure 3-29b: CMOS (MOSFET) gate transistor design examples [3-12]

In the static CMOS (complementary metal-oxide semiconductor) logic method of implementing gates, both nMOS and pMOS gates are used in the design. (For simplicity and electrical reasons, transistors of the same polarity are often not mixed, but grouped separately, where transistors of one polarity type pull output a certain way with some input value, and the other pulls output the other way, given the same input.) The CMOS method is sequential-based, meaning there are no clocks in the circuit, and that circuit outputs are based upon all past and current inputs (as opposed to the combinatorial method whose output is based upon input at some moment in time). Sequential vs. combinatorial gates will be discussed in more detail later this section. The NOT Gate is simplest to understand, so we start with this example.

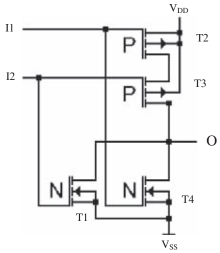
***Note: inputs (I1 and I2) are inputs to the transistor gates. For P-channel (pMOS) enhancement transistors, the transistor is ON when gate is OFF, whereas for the N-channel (nMOS) enhancement transistor the transistor is ON when gate is ON.*



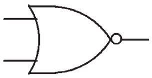
0, nMOS T2 is OFF -- pMOS T1 is ON -- and with V_{DD} will pull O =1.
1, pMOS T1 is OFF -- nMOS T2 is ON -- but Vss/Gnd will pull O = 0.

Figure 3-29b: CMOS (MOSFET) gate transistor design examples [3-12] (continued)

NOR Gate



Schematic Symbol



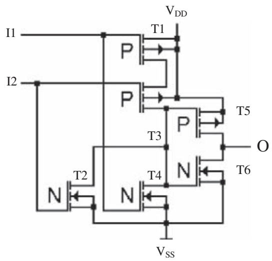
I1 = 0 , I2 = 0 then O = 1
When I1 = 0 pMOS T2 is ON (pulled up by V_{DD}) – nMOS T4 is OFF
I2 = 0 nMOS T1 is OFF -- pMOS T3 is ON(pulled up by V_{DD})
O determined by T1, T3, or T4 being ON – so O = 1 since T3 is ON

I1 = 0 , I2 = 1 then O = 0
When I1 = 0 pMOS T2 is ON (pulled up by V_{DD}) – nMOS T4 is OFF
I2 = 1 nMOS T1 is ON but pulled to 0 by Vss/GND -- pMOS T3 is OFF
O determined by T1, T3, or T4 being ON – so O = 0 since no transistors pulled ON

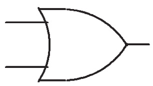
I1 = 1 , I2 = 0 then O = 0
When I1 = 1 pMOS T2 is OFF – nMOS T4 is ON but pulled to 0 by Vss/GND
I2 = 0 nMOS T1 is OFF -- pMOS T3 is ON(pulled up by V_{DD})
O determined by T1, T3, or T4 being ON – so O = 0 since no transistors pulled ON

I1 = 1 , I2 = 1 then O = 0
When I1 = 1 pMOS T2 is OFF – nMOS T4 is ON but pulled to 0 by Vss/GND
I2 = 1 nMOS T1 is ON but pulled to 0 by Vss/GND -- pMOS T3 is OFF
O determined by T1, T3, or T4 being ON – so O = 0 since no transistors pulled ON

OR Gate



Schematic Symbol



Note : This is circuit is a NOR gate with an inverter at the end of circuit.(T5 and T6)

I1 = 0, I2 = 0 then O = 0
I1 (0) “NOR” I2 (0) resulted in O=1, thus inverted is O=0

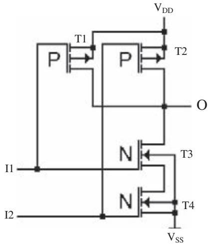
I1 = 0 , I2 = 1 then O = 1
I1(0) “NOR” I2 (1) Resulted in O=0, thus inverted is O = 1

I1 = 1 , I2 = 0 then O = 1
I1(1) “NOR” I2 (0) Resulted in O=0, thus inverted is O = 1

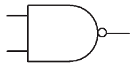
I1 = 1 , I2 = 1 then O = 1
I1(1) “NOR” I2 (1) Resulted in O=0, thus inverted is O = 1

Figure 3-29b: CMOS (MOSFET) gate transistor design examples [3-12] (continued)

NAND Gate



Schematic Symbol



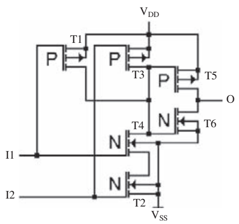
I1 = 0 , I2 = 0 then O = 1
When I1 = 0 pMOS T1 is ON (pulled up by V_{DD}) – nMOS T3 is OFF
I2 = 0 nMOS T4 is OFF -- pMOS T2 is ON(pulled up by V_{DD})
O determined by T1, T2, or T3 being ON – so O = 1 since T1 and T2 is ON

I1 = 0 , I2 = 1 then O = 1
When I1 = 0 pMOS T1 is ON (pulled up by V_{DD}) – nMOS T3 is OFF
I2 = 1 nMOS T4 is ON but pulled to 0 by Vss/GND -- pMOS T2 is OFF
O determined by T1, T2, or T3 being ON – so O = 1 since T1 is ON

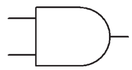
I1 = 1 , I2 = 0 then O = 1
When I1 = 1 pMOS T1 is OFF – nMOS T3 is ON but pulled to 0 by Vss/GND
I2 = 0 nMOS T4 is OFF -- pMOS T2 is ON(pulled up by V_{DD})
O determined by T1, T2, or T3 being ON – so O = 1 since T2 is ON

I1 = 1 , I2 = 1 then O = 0
When I1 = 1 pMOS T1 is OFF – nMOS T3 is ON but pulled to 0 by Vss/GND
I2 = 1 nMOS T4 is ON but pulled to 0 by Vss/GND -- pMOS T2 is OFF
O determined by T1, T2, or T3 being ON – so O = 0 since no transistors pulled ON

AND Gate



Schematic Symbol



Note : This is circuit is a NAND gate with an inverter a t the end of circuit.(T5 and T6)

I1 = 0, I2 = 0 then O = 0
I1 (0) “NAND” I2 (0) resulted in O=1, thus inverted is O=0

I1 = 0 , I2 = 1 then O = 0
I1(0) “NAND” I2 (1) Resulted in O=1, thus inverted is O = 0

I1 = 1 , I2 = 0 then O = 0
I1(1) “NAND” I2 (0) Resulted in O=1, thus inverted is O = 0

I1 = 1 , I2 = 1 then O = 1
I1(1) “NAND” I2 (1) Resulted in O=0, thus inverted is O = 1

Sequential Logic and the Clock

Logic gates can be combined in many different ways to perform more useful and complex logic circuits (called ***sequential logic***), such as circuits that have some type of memory. In order to accomplish this, there must be a *sequential* series of procedures to be followed to store and retrieve data at any moment in time. Sequential logic is typically based upon one of two models: a ***sequential*** or ***combinational*** circuit design. These models differ in what triggers their gate(s) into changing state, as well as what the results are of a changed state (output). All gates exist in some defined "state," which is defined as the current values associated with the gate, as well as any behavior associated with the gate when the values change.

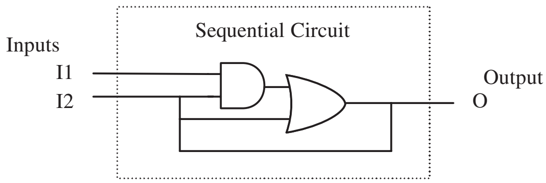


Figure 3-30: Sequential circuit diagram

As shown in Figure 3-30, sequential circuits provide output that can be based upon current input values, as well as previous input and output values in a feedback loop. Sequential circuits can change states *synchronously* or a*synchronously* depending on the circuit. Asynchronous sequential circuits change states only when the inputs change. Synchronous sequential circuits change states based upon a *clock signal* generated by a ***clock generator*** connected to the circuit.

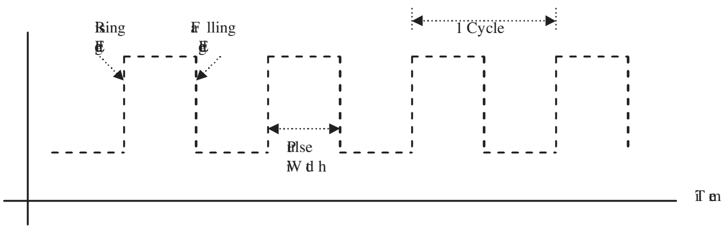


Figure 3-31: Clock signal of synchronous sequential circuits

Almost every embedded board has an oscillator, a circuit whose sole purpose is generating a repetitive signal of some type. Digital clock generators, or simply clocks, are oscillators that generate signals with a square waveform (see Figure 3-31). Different components may require oscillators that generate signals of various waveforms, such as sinusoidal, pulsed, saw tooth, and so on to drive them. In the case of components driven by a digital clock, it is the square waveform. The waveform forms a square, because the clock signal is a logical signal that continuously changes from 0 to 1 or 1 to 0. The output of the synchronous sequential circuit is synchronized with that clock.

Commonly used sequential circuits (synchronous and asynchronous) are multivibrators, logic circuits designed so that one or more of its outputs are fed back as input. The subtypes of multivibrators—astable, monostable or bistable—are based upon the *states* in which they hold stable. Monostable (or oneshot) multivibrators are circuits that have only one stable state, and produce one output in response to some input. The bistable multivibrator has two stable states (0 or 1), and can remain in either state indefinitely, whereas the astable multivibrator has no state in which it can hold stable. ***Latches*** are examples of bistable multivibrators. Latches are multivibrators, because signals from the output are fed back into inputs, and they are bistable because they have only one of two possible output states they can hold stable at: 0 or 1. Latches come in several different subtypes (S-R, Gated S-R, D Latch, etc.). Figure 3-32 demonstrates how the basic logical gates are combined to make different types of latches.

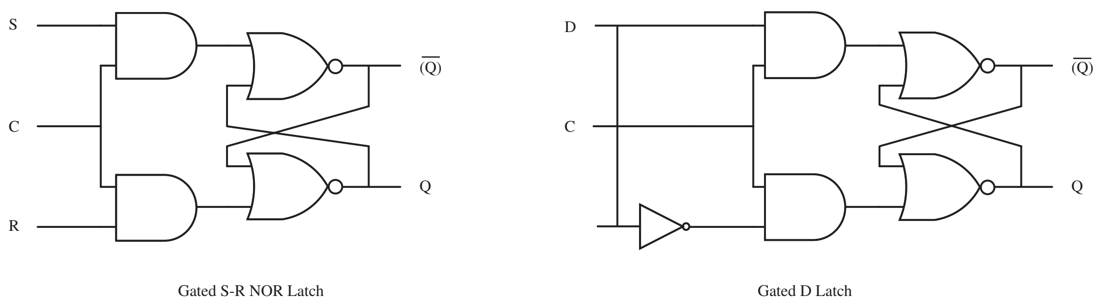


Figure 3-32: Latches [3-8]

One of the most commonly used types of latches in processors and memory circuitry is the ***flip-flop***. Flip-flops are sequential circuits that derived their name because they function by alternating (flip-flopping) between both states (0 and 1), and the output is then switched (from 0-to-1 or from 1-to-0, for example). There are several types of flip-flops, but all essentially fall under either the asynchronous or synchronous categories. Flip-flops, and most sequential logic, can be made from a variety of different gate combinations, all achieving the same type of results. Figure 3-33 is an example of a synchronous flip-flop, specifically an edge-triggered D flip-flop. This type of flip-flop changes state on the rising edge or falling edge of a square-wave enable signal—in other words, it only changes states, thus changing the output, when it receives a *trigger* from a clock.

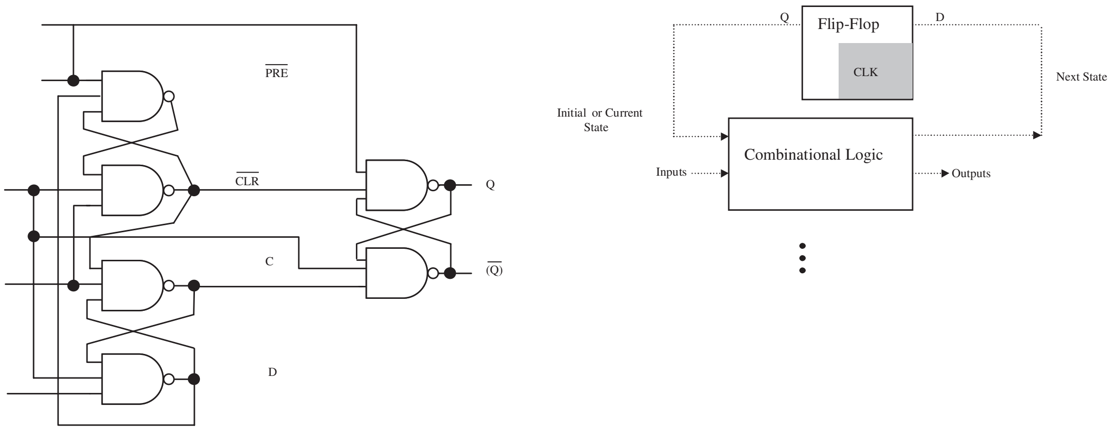


Figure 3-33: D flip-flop diagram [3-8]

Like the sequential circuit, combinational circuits can have one or more input(s) and only one output. However, both models primarily differ in that a combinatorial circuit's output is dependent only on inputs applied at that instant, as a function of time, and "no" past conditions. A sequential circuit's output, on the other hand, can be based upon previous outputs being fed back into the input, for instance. Figure 3-34 shows an example of a combinational circuit, which is essentially a circuit with no feedback loop.

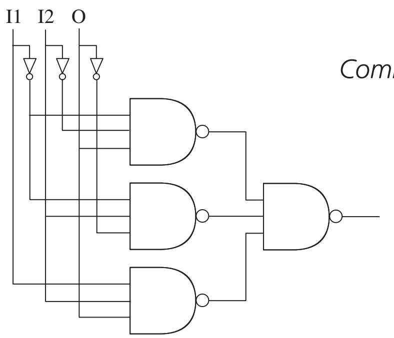


Figure 3-34: Combinational circuit (no feedback loop) [3-9]

All of the various logic gates introduced in the last sections, along with the other electronic devices discussed in this chapter so far, are the building blocks of more complex circuits that implement everything from the storage of data in memory to the mathematical computations performed on data within a processor. Memory and processors are all inherently complex circuits, explicitly ***integrated circuits*** (ICs).

3.7 Putting It All Together: The Integrated Circuit (IC)

Gates, along with the other electronic devices that can be located on a circuit, can be compacted to form a single device, called an ***integrated circuit*** (IC). ICs, also referred to as ***chips***, are usually classified into groups according to the number of transistors and other electronic components they contain, as follows:

- **SSI** (small scale integration) containing up to 100 electronic components per chip.
- **MSI** (medium scale integration) containing between 100–3,000 electronic components per chip.
- **LSI** (large scale integration) containing 3,000–100,000 electronic components per chip.
- **VLSI** (very large scale integration) containing between 100,000–1,000,000 electronic components per chip.
- **ULSI** (ultra large scale integration) containing over 1,000,000 electronic components per chip.

ICs are physically enclosed in a variety of packages that includes SIP, DIP, flat pack, and others. (See Figure 3-35.) They basically appear as boxes with pins protruding from the body of the box. The pins connect the IC to the rest of the board.

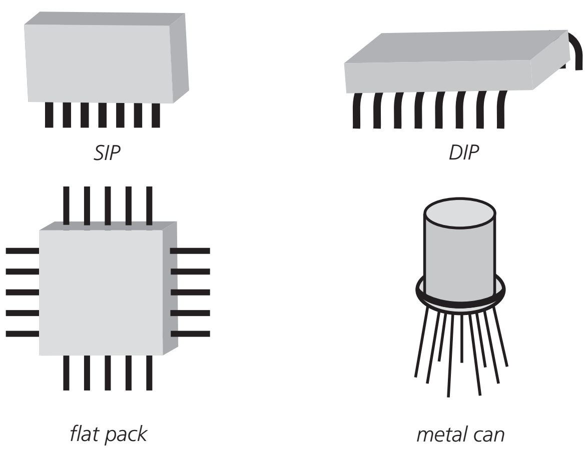
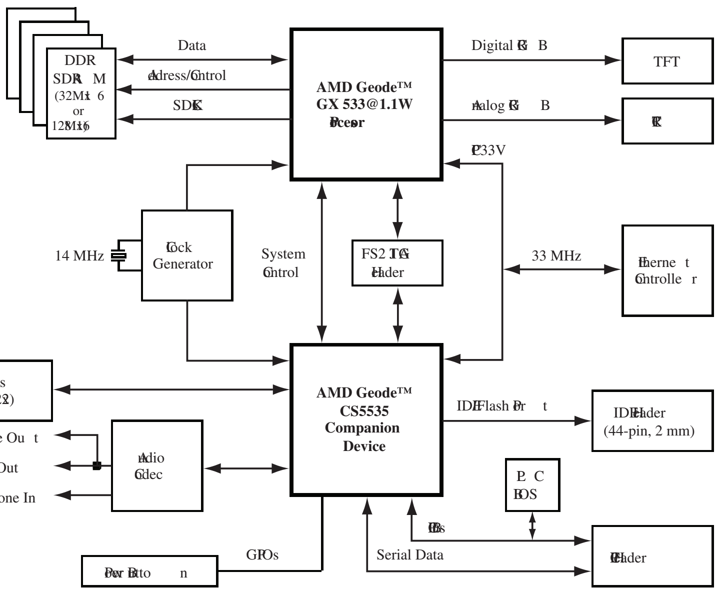


Figure 3-35: IC packages

Physically packaging so many electronic components in an IC has its advantages as well as drawbacks. These include:

- *Size.* ICs are much more compact than their discrete counterparts, allowing for smaller and more advanced designs.
- *Speed*. The buses interconnecting the various IC components are much, much smaller (and thus faster) than on a circuit with the equivalent discrete parts.
- *Power*. ICs typically consume much less power than their discrete counterparts.
- *Reliability*. Packaging typically protects IC components from interference (dirt, heat, corrosion, etc.) far better than if these components were located discretely on a board.
- *Debugging*. It is usually simpler to replace one IC than try to track down one component that failed among 100,000 (for example) components.
- *Usability.* Not all components can be put into an IC, especially those components that generate a large amount of heat, such as higher value inductors or high-powered amplifiers.

In short, ICs are the master processors, slave processors, and memory chips located on embedded boards (see Figure 3-36a through e).



- **Master Processor**: Geode GX533@1.1w (x86)
- **Memory**: ROM (BIOS is located in), SDRAM
- **Input/Output Devices**: CS5535, Audio Codec...
- **Buses**: LPC, PCI

Figure 3-36a: AMD/National Semiconductor x86 reference board [3-1]

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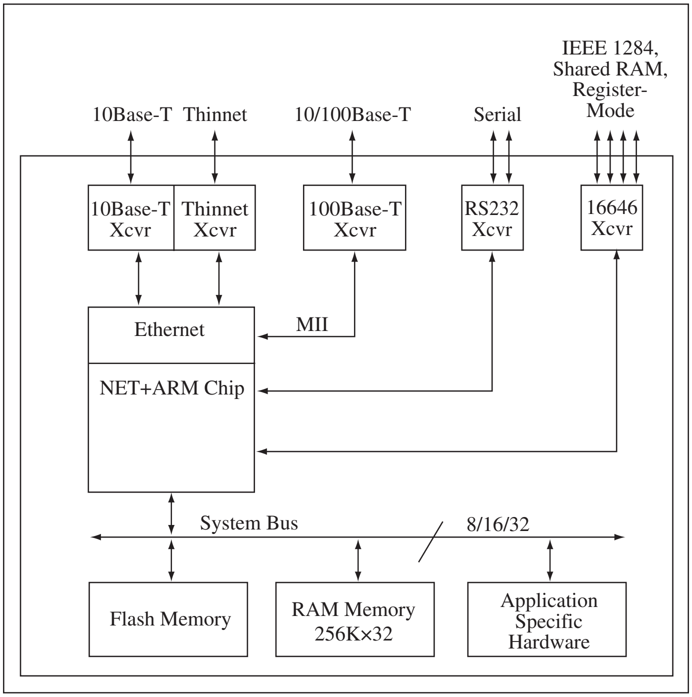


Figure 3-36b: Net Silicon ARM7 reference board [3-2]

ICs

- **Master Processor**: Net+ARM ARM7
- **Memory:** Flash, RAM
- **Input/Output Devices**: 10Base-T transceiver, Thinnet transceiver, 100Base-T transceiver, RS-232 transceiver, 16646 transceiver, etc.

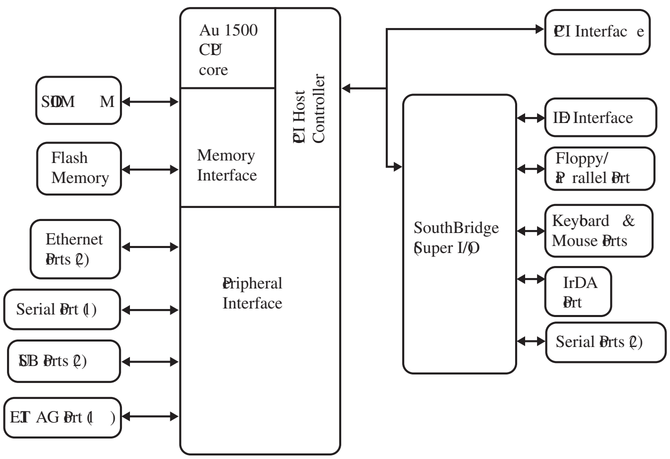
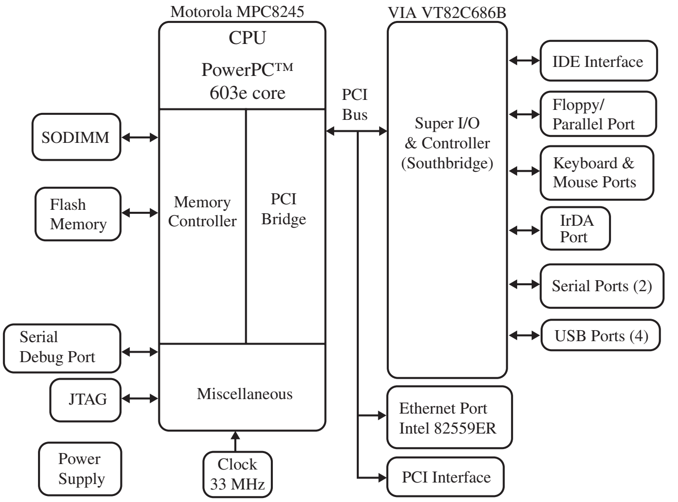


Figure 3-36c: Ampro MIPS reference board [3-3]

ICs

- **Master Processor**: Encore M3 (Au1500-based) processor
- **Memory:** Flash, SODIMM
- **Input/Output Devices**: Super I/O, etc.



ICs

- **Master Processor**: MPC8245
- **Memory:** Flash, SODIMM
- **Input/Output Devices**: Super I/O, 82559 Transceiver, etc.

Figure 3-36d: Ampro PowerPC reference board [3-4]

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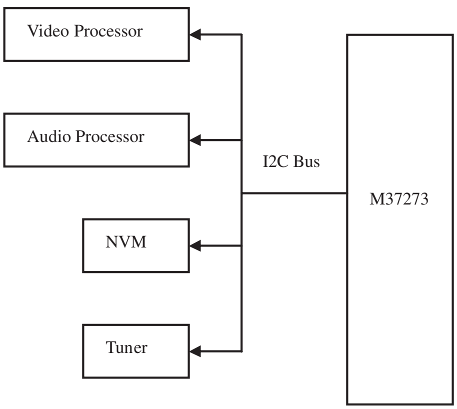

ICs

- **Master Processor**: M37273 (8-bit) TV microcontroller
- **Memory:** NVM
- **Input/Output Devices**: Video processor, audio processor, tuner, etc.

Figure 3-36e: Mitsubishi analog TV reference board

3.8 Summary

The purpose of this chapter was to discuss the major functional hardware components of an embedded board. These components were defined as the master processor, memory, I/O, and buses—the basic components that make up the von Neumann model. The passive and active electrical elements that make up the von Neumann components, such as resistors, capacitors, diodes, and transistors, were also discussed in this chapter. It was demonstrated how these basic components can be used to build more complex circuitry, such as gates, flip-flops, and ICs, that can be integrated onto an embedded board. Finally, the importance of and how to read hardware technical documentation, such as timing diagrams and schematics, was introduced and discussed.

The next chapter, *Chapter 4: Embedded Processors*, covers the design details of embedded processors by introducing the different ISA models, as well as how the von Neumann model is applicable to implementing an ISA in the internal design of a processor.

Chapter 3 Problems

1. [a] What is the von Neumann model?
   [b] What are the main elements defined by the von Neumann model?
   [c] Given the block diagrams in Figures 3-37a and b, and data sheet information on the accompanying CD under Chapter 3, files "ePMC-PPC" and "sbcARM7", identify where the major elements in this diagram would fall relative to the von Neumann model.

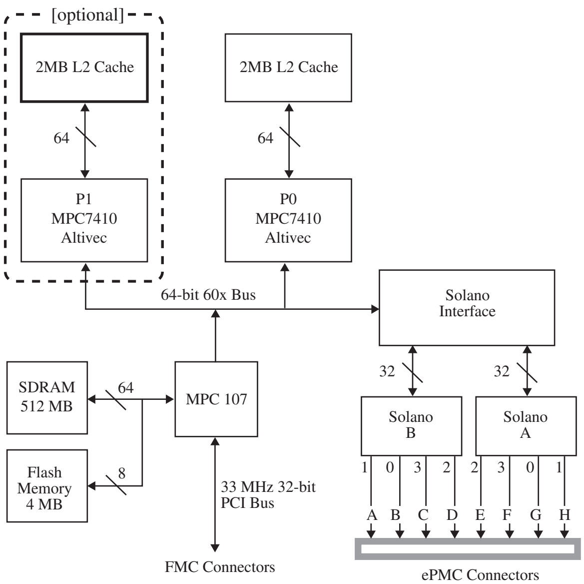

Figure 3-37a: PowerPC board block diagram [3-13]

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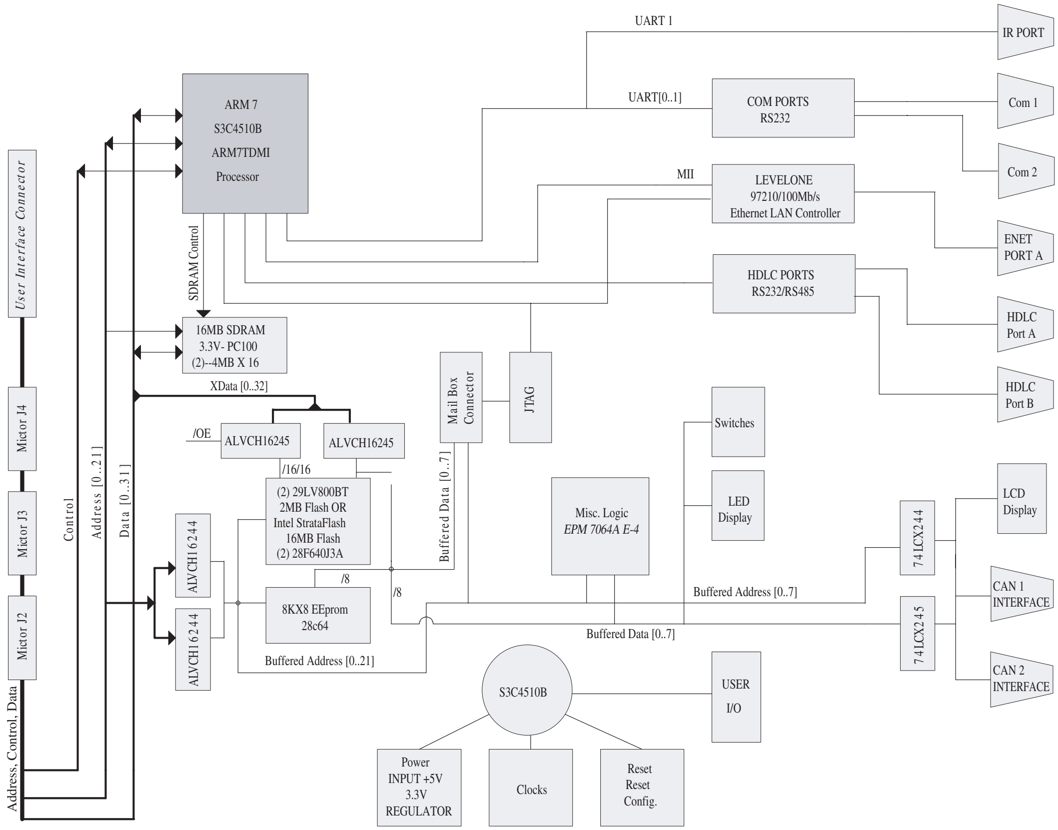


Figure 3-37b: ARM board block diagram [3-14]

2. [a] Given the simple flashlight shown in Figure 3-38, draw a corresponding schematic diagram.

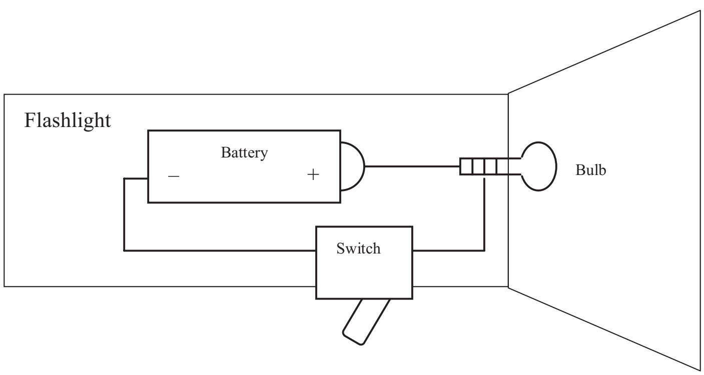


Figure 3-38: Simple flashlight [3-15]

[b] Read the schematic diagram in Figure 3-39, and identify the symbols in the diagram.

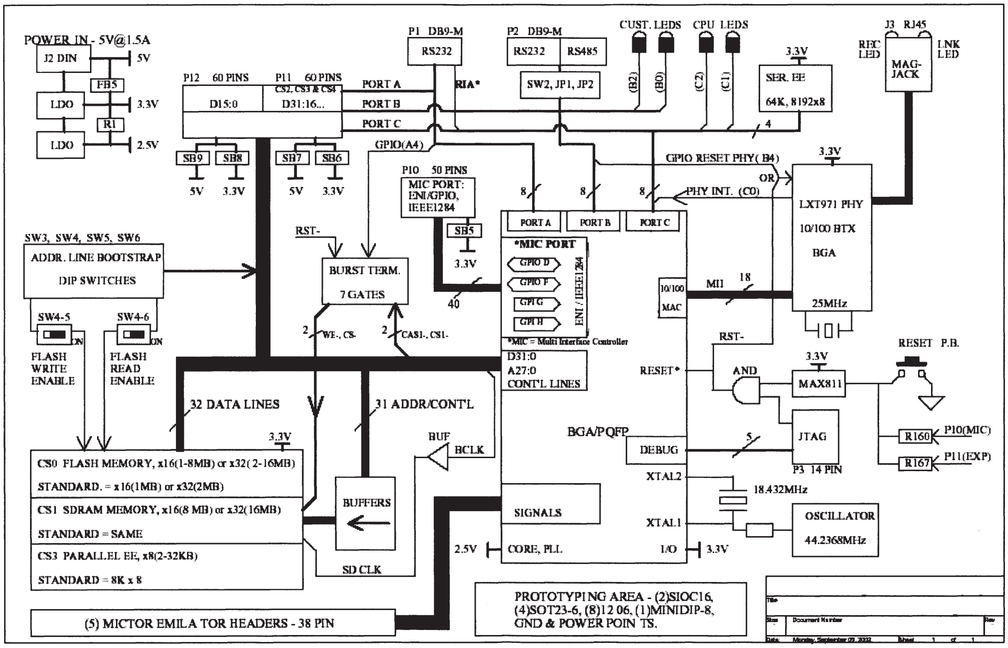


Figure 3-39: Schematic diagram example [3-7]

3. [a] What are the basic materials that all components on an embedded board are composed of?
   [b] What are the major differences between these materials?
   [c] Give two examples of each type of material.

4. Finish the sentence: A wire is:
   A. not an insulator.
   B. a conductor.
   C. a semiconductor.
   D. Both A and B.
   E. None of the above.

5. [T/F] A surplus of electrons exists in a P-type semiconductor.

6. [a] What is the difference between a passive circuit element and an active circuit element?
   [b] Name three examples of each.

7. [a] Define and explain the various properties of the fixed resistor in Figure 3-40 by reading its color-coded bands and referencing Tables 3-3 a, b, c, and d.
   [b] Calculate its resistance.

Color of Band	Digits	Multiplier
Black	0	×1
Brown	1	×10
Red	2	×100
Orange	3	×1K
Yellow	4	×10K
Green	5	×100K
Blue	6	×1M
Purple	7	×10M
Grey	8	×100M
White	9	×1000M
Silver	-	×0.01
Gold	-	×0.1

Table 3-3a: Resistor color code digits and multiplier table [3-6]

Color of Band	Temperature coefficient
Brown	100 ppm
Red	50 ppm
Orange	15 ppm
Yellow	25 ppm

Table 3-3b: Temperature coefficient [3-6]

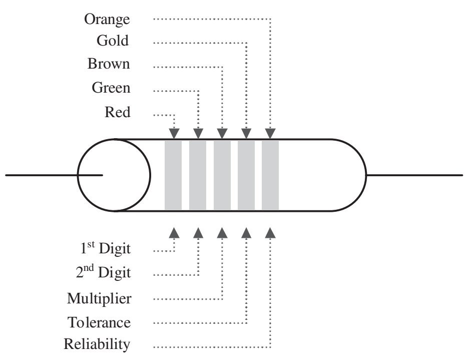
Color of Band	Reliability Level (%)
Brown	1%
Red	0.1%
Orange	0.01%
Yellow	0.001%

Table 3-3c: Reliability level (%1000 HR) [3-6]

Color of Band	Tolerance (%)
Silver	± 10%
Gold	± 5%
Brown	± 1%
Red	± 2%
Green	± 0.5%
Blue	± 0.25%
Purple	± 0.1%

Table 3-3d: Tolerance [3-6]

Figure 3-40: Fixed resistor



8. Where do capacitors store energy?
   A. In magnetic fields.
   B. In electric fields.
   D. None of the above.
   E. All of the above.

9. [a] Where do inductors store energy?
   [b] What happens to an inductor when the current stream changes?

10. What feature does not affect the inductance of a wire?
    A. The diameter of the wire.
    B. The diameter of the coils.
    B. The number of individual coils.
    C. The type of material the wire is made of.
    D. The overall length of the coiled wire.
    E. None of the above.

11. What is the PN junction?

12. [a] What is an LED?
    [b] How does an LED work?

13. [a] What is a transistor?
    [b] What is a transistor made of?

14. [T/F] The NPN-BJT transistor shown in Figure 3-41 is OFF.

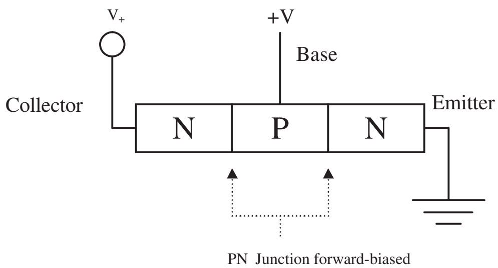


Figure 3-41: NPN BJT transistor

15. Which figure, of Figures 3-42a through d, shows a P-channel depletion MOSFET that is ON?

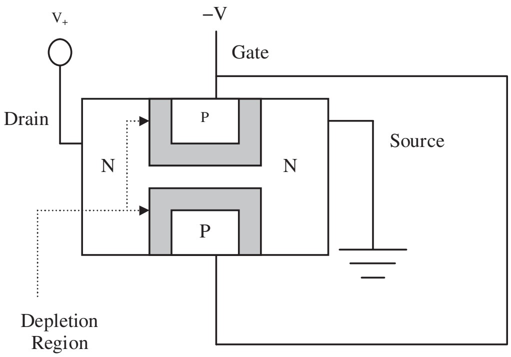


Figure 3-42a: MOSFET 1

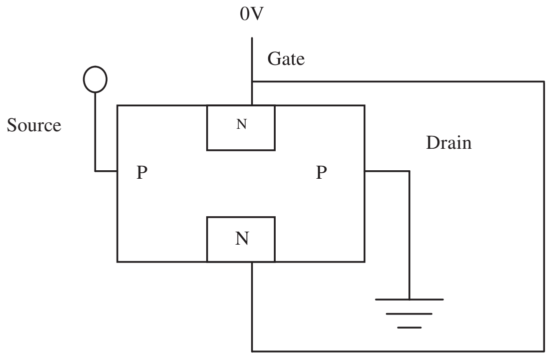


Figure 3-42b: MOSFET 2

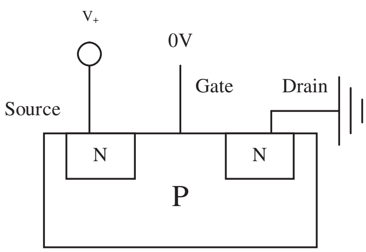


Figure 3-42c: MOSFET 3

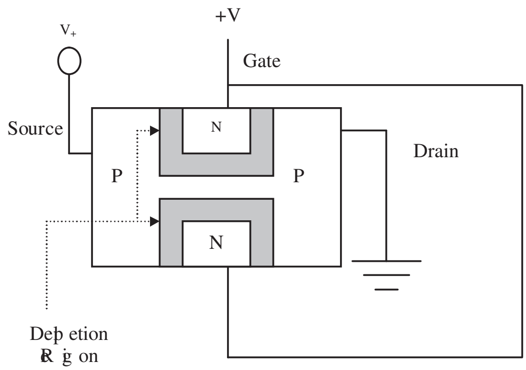


Figure 3-42d: MOSFET 4

16. [a] What are gates?
    [b] What are gates typically designed to perform?
    [c] Draw the truth tables for the logical binary operations NOT, NAND, and AND.

17. [a] Draw and describe a NOT gate built from CMOS (MOSFET) transistors.
    [b] Draw and describe a NAND gate built from CMOS (MOSFET) transistors.
    [c] Draw and describe an AND gate built from CMOS (MOSFET) transistors. [Hint: this circuit is a NAND gate with an inverter at the end of the circuit.]

18. What is a flip-flop?

19 [a] What is an IC?

[b] Name and describe the classes of ICs according to the number of electronic components they contain.

20. Identify at least five ICs in Figures 3-37a and b under problem 1 of this section.