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Foreword

Aim of This Textbook

Electronics | Foreword | Basic Electronics | Complex Electronics | Electricity | Machines | History of Electronics | Appendix | edit

The aim of this textbook is to explain the design and function of electronic circuits and components. The text covers electronic circuit components, DC analysis, and AC analysis.

It should be useful to beginner hobbyists as well as beginner engineering students, teaching both theory and practical applications.

It should be thought of as a companion project to the Wikipedia articles about electronics. While the Wikipedia covers many details about the technology used in electronics components and related fields, the Electronics Wikibook covers a lot of the "how-to" aspects that aren't covered in an encyclopedia. The book will focus on how to use the components to build useful circuits.

Prerequisites

Prerequisite Topics

Most important / Required knowledge

Moderately Important / Aids in comprehension

Slightly Important / Related or helpful

Mathematics

- Algebra
- Calculus
- Multivariable Calculus
- Geometry

Physics

Preface

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Importance of Electronics

Electronics is the study and use of devices that control the flow of electrons (or other charged particles). These devices can be used to process information or perform tasks using electromagnetic power.

Electronic circuits can be found in numerous household products, including such items as telephones, computers, and CD players. Electronic devices have also allowed greatly increased precision in scientific measurements.

Interest in the field of electronics increased around 1900 and the advent of radio. Interest reached an all-time high in the 1940s, 50s, 60s, with the invention of transistor radios, the launch of Sputnik, and the science and math educational push to win the space race. Interest in electronics as a hobby in the 1970s led to the advent of the personal computer (PC).

Electronics have since seen a decline in hobbyist interest. Electronics is now generally studied as part of a college-level program in electrical engineering.

This book is an attempt at reviving the hobbyist mentality that made electronics so big in the first place, by making electronics concepts more accessible and giving practical knowledge, as well as providing technical information for the student.

Charge and Coulomb's Law

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> Two atoms are walking down the street. The first atom says to the second atom "I think I lost an electron!" The second says "Are you sure?" To which the first states "I'm **positive**!"

Basic Understanding

Conductors
: Materials which contain movable charges that can flow with minimal resistance.

Insulators
: Materials with few or no movable charges, or with charges which flow with extremely high resistance.

Semiconductors
: Materials whose behavior ranges between that of a conductor and that of an insulator under different conditions. Their conducting behavior may be heavily dependent on temperature. They are useful because we are able to change their conducting behavior to be dependent on many other factors.

The Atom

An atom contains a positively charged nucleus and one or more negatively charged electrons. The atom exists in three states: neutral, positively charged, and negatively charged. A neutral atom has the same number of electrons and protons, a positively charged atom has more protons than electrons and a negatively charged atom has more electrons than protons.

(+) and (-) Ions

An ion is an atom that has an unequal number of electrons and protons. Ions are formed when a neutral atom gains or loses electrons during a chemical reaction. In a battery, the positive side has + ions, means there are fewer electrons than protons, giving it an overall positive charge, and -ve side, more electrons than protons, giving it an overall negative charge. +ve and -ve charge will attract each other, and it is the use of such an attractive force that allows the battery to do work.

Note: Electric current is not the same as electron flow as is widely mistaken. Firstly, the total current has the opposite direction compared to electron flow. This is a lucky "mistake" on our forefathers' part to put it this way. It is also because of this lucky legacy that we are reminded that electricity can flow in materials other than metals alone. For example, in water, it is not electrons that flow, it is ions, and the +ve ions and -ve ions flow in opposite directions, contributing half of the total current each.

Balance of Charge

Atoms, the smallest particles of matter that retain the properties of the matter, are made of protons, electrons, and neutrons. **Protons** have a positive charge, **Electrons** have a negative charge that cancels the proton's positive charge. **Neutrons** are particles that are similar to a proton but have a neutral charge. There are no differences between positive and negative charges except that particles with the same charge **repel** each other and particles with opposite charges **attract** each other. If a solitary positive proton and negative electron are placed near each other they will come together to form a hydrogen atom. This repulsion and attraction (force between stationary charged particles) is known as the **Electrostatic Force** and extends theoretically to infinity, but is diluted as the distance between particles increases.

When an atom has one or more missing electrons it is left with a **positive** charge, and when an atom has at least one extra electron it has a **negative** charge. Having a positive or a negative charge makes an atom an **ion**. Atoms only gain and lose protons and neutrons through fusion, fission, and radioactive decay. Although atoms are made of many particles and objects are made of many atoms, they behave similarly to charged particles in terms of how they repel and attract.

In an **atom** the protons and neutrons combine to form a tightly bound nucleus. This nucleus is surrounded by a vast cloud of electrons circling it at a distance but held near the protons by electromagnetic attraction (the electrostatic force discussed earlier). The cloud exists as a series of overlapping **shells / bands** in which the inner **valence** bands are filled with electrons and are tightly bound to the atom. The outer **conduction** bands contain no electrons except those that have accelerated to the conduction bands by gaining energy. With enough energy an electron will escape an atom (compare with the escape velocity of a space rocket). When an electron in the conduction band decelerates and falls to another conduction band or the valence band a photon is emitted. This is known as the **photoelectric effect**.

A **laser** is formed when electrons travel back and forth between conduction bands emitting synchronized photons.

1. When the conduction and valence bands overlap, the atom is a **conductor** and allows for the free movement of electrons. Conductors are metals and can be thought of as a bunch of atomic nuclei surrounded by a churning "sea of electrons".
2. When there is a large energy level gap between the conduction and valence bands, the atom is an **insulator**; it traps electrons. Many insulators are non-metals and are good at blocking the flow of electrons.

3. When there is a small energy level gap between the conduction and valence bands, the atom is a **semiconductor**. Semiconductors behave like conductors and insulators, and work using the conduction and valence bands. The electrons in the outer valence band are known as **holes**. They behave like positive charges because of how they flow. In semiconductors electrons collide with the material and their progress is halted. This makes the electrons have an **effective mass** that is less than their normal mass. In some semiconductors holes have a larger effective mass than the conduction electrons.

Electronic devices are based on the idea of exploiting the differences between conductors, insulators, and semiconductors but also exploit known physical phenomena such as electromagnetism and phosphorescence.

Conductors

In a metal the electrons of an object are free to move from atom to atom. Due to their mutual repulsion (calculable via Coulomb's Law), the valence electrons are forced from the centre of the object and spread out evenly across its surface in order to be as far apart as possible. This **cavity** of empty space is known as a **Faraday Cage** and stops **electromagnetic radiation**, such as charge, radio waves, and **EMPs** (Electro-Magnetic Pulses) from entering and leaving the object. If there are holes in the Faraday Cage then radiation can pass.

One of the interesting things to do with conductors is demonstrate the transfer of charge between metal spheres. Start by taking two identical and uncharged metal spheres which are each suspended by insulators (such as a pieces of string). The first step involves putting sphere 1 next to but not touching sphere 2. This causes all the electrons in sphere 2 to travel away from sphere 1 to the far end of sphere 2. So sphere 2 now has a negative end filled with electrons and a positive end lacking electrons. Next sphere 2 is **grounded** by contact with a conductor connected with the earth and the earth takes its electrons leaving sphere 2 with a positive charge. The positive charge (absence of electrons) spreads evenly across the surface due to its lack of electrons. If suspended by strings, the relatively negatively charged sphere 1 will attract the relatively positively charged sphere 2.

Insulators

In an insulator the charges of a material are stuck and cannot flow. This allows an imbalance of charge to build up on the surface of the object by way of the triboelectric effect. The **triboelectric effect** (rubbing electricity effect) involves the exchange of electrons when two different insulators such as glass, hard rubber, amber, or even the seat of one's trousers, come into contact. The polarity and strength of the charges produced differ according to the material composition and its surface smoothness. For example, glass rubbed with silk will build up a charge, as will hard rubber rubbed with fur. The effect is greatly enhanced by rubbing materials together.

- **Van de Graaff Generator:** A **charge pump** (pump for electrons) that generates static electricity. In a Van de Graaff generator, a conveyor belt uses rubbing to pick up electrons, which are then deposited on metal brushes. The end result is a charge difference.

Because the material being rubbed is now charged, contact with an uncharged object or an object with the opposite charge may cause a discharge of the built-up **static electricity** by way of a spark. A person simply walking across a carpet may build up enough charge to cause a spark to travel over a centimetre. The spark is powerful enough to attract dust particles to cloth, destroy electrical equipment, ignite gas fumes, and create lightning. In extreme cases the spark can destroy factories that deal with gunpowder and explosives. The best way to remove static electricity is by discharging it through grounding. Humid air will also slowly discharge static electricity. This is one reason cells and capacitors lose charge over time.

Note: The concept of an insulator changes depending on the applied voltage. Air looks like an insulator when a low voltage is applied. But it breaks down as an insulator, becomes ionised, at about ten kilovolts per centimetre. A person could put their shoe across the terminals of a car battery and it would look like an insulator. But putting a shoe across a ten kilovolt powerline will cause a short.

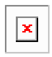
Quantity of Charge

Protons and electrons have opposite but equal charge. Because in almost all cases, the charge on protons or electrons is the smallest amount of charge commonly discussed, the quantity of charge of one proton is considered one positive **elementary charge** and the charge of one electron is one negative **elementary charge**. Because atoms and such particles are so small, and charge in amounts of multi-trillions of elementary charges are usually discussed, a much larger unit of charge is typically used. The **coulomb** is a unit of charge, which can be expressed as a positive or negative number, which is equal to approximately 6.2415×10^{18} elementary charges. Accordingly, an elementary charge is equal to approximately 1.602×10^{-19} coulombs. The commonly used abbreviation for the coulomb is a capital **C**. The SI definition of a coulomb is the quantity of charge which passes a point over a period of 1 second (s) when a current of 1 ampere (A) flows past that point, i.e., C = A·s or A = C/s. You may find it helpful during later lessons to retain this picture in your mind (even though you may not recall the exact number). An ampere is one of the fundamental units in physics from which various other units are defined, such as the coulomb.

Force between Charges: Coulomb's Law

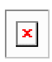
The repulsive or attractive **electrostatic force** between charges decreases as the charges are located further from each other by the square of the distance between them. An equation called **Coulomb's law** determines the electrostatic force between two charged objects. The following picture shows a charge q at a certain point with another charge Q at a distance of r away from it. The presence of Q causes an electrostatic force to be exerted on q.

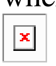
The magnitude of the electrostatic force F, on a charge q, due to another charge Q, equals **Coulomb's constant** multiplied by the product of the two charges (in coulombs) divided by the square of the distance r, between the charges q and Q. Here a capital Q and small q are scalar quantities used for symbolizing the two charges, but other symbols such as q_1 and q_2 have been used in other sources. These symbols for charge were used for consistency with the electric field article in Wikipedia and are consistent with the Reference below.

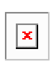


F = magnitude of electrostatic force on charge q due to another charge Q
r = distance (magnitude quantity in above equation) between q and Q
k = Coulomb's constant = 8.9875×10^9 N·m^2/C^2 in free space

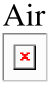
The value of Coulomb's constant given here is such that the preceding Coulomb's Law equation will work if both q and Q are given in units of coulombs, r in metres, and F in newtons and there is no dielectric material between the charges. A **dielectric material** is one that reduces the electrostatic force when placed between charges. Furthermore, Coulomb's constant can be given by:



where

= **permittivity**. When there is no dielectric material between the charges (for example, in free space or a vacuum),



= 8.85419×10^{-12} C^2/(N·m^2).

Air is only very weakly dielectric and the value above for


will work well enough with air between the charges. If a dielectric material is present, then

where

is the **dielectric constant** which depends on the dielectric material. In a vacuum (free space),

and thus

. For air,

. Typically, solid insulating materials have values of

and will reduce electric force between charges. The dielectric constant can also be called **relative permittivity**, symbolized as

in Wikipedia.

Highly charged particles close to each other exert heavy forces on each other; if the charges are less or they are farther apart, the force is less. As the charges move far enough apart, their effect on each other becomes negligible.

Any force on an object is a vector quantity. Vector quantities such as forces are characterized by a numerical magnitude (i. e. basically the size of the force) and a direction. A vector is often pictured by an arrow pointing in the direction. In a force vector, the direction is the one in which the force pulls the object. The symbol

is used here for the electric force vector. If charges q and Q are either both positive or both negative, then they will repel each other. This means the direction of the electric force on *q* due to *Q* is away from *Q* in exactly the opposite direction, as shown by the red arrow in the preceding diagram. If one of the charges is positive and the other negative, then they will attract each other. This means that the direction of

on *q* due to *Q* is exactly in the direction towards *Q*, as shown by the blue arrow in the preceding diagram. The Coulomb's equation shown above will give a magnitude for a repulsive force away from the *Q* charge. A property of a vector is that if its magnitude is negative, the vector will be equal to a vector with an equivalent but positive magnitude and exactly the opposite direction. So, if the magnitude given by the above equation is negative due to opposite charges, the direction of the resulting force will be directly opposite of away from *Q*, meaning the force will be towards *Q*, an attractive force. In other sources, different variations of Coulombs' Law are given, including vector formulas in some cases (see Wikipedia link and reference(s) below).

In many situations, there may be many charges, Q_1, Q_2, Q_3, through Q_n, on the charge *q* in question. Each of the Q_1 through Q_n charges will exert an electric force on *q*. The direction of the force depends on the location of the surrounding charges. A Coulomb's Law calculation between *q* and a corresponding Q_i charge would give the magnitude of the electric force exerted by each of the Q_i charges for $i = 1$ through *n*, **but** the direction of each of the component forces must also be used to determine the individual force vectors,

. To determine the total electric force on *q*, the electric force contributions from each of these charges add up as **vector** quantities, not just like ordinary (or scalar) numbers.

The total electric force on *q* is additive to any other forces affecting it, but all of the forces are to be added together as **vectors** to obtain the total force on the charged object *q*. In many cases, there are billions of electrons or other charges present, so that geometrical distributions of charges are used with equations stemming from Coulomb's Law. Practically speaking, such calculations are usually of more interest to a physicist than an electrician, electrical engineer, or electronics hobbyist, so they will not be discussed much more in this book, except in the section on capacitors.

In addition to the electrostatic forces described here, electromagnetic forces are created when the charges are moving. These will be described later.

Reference(s):

- College Physics Volume 2 by Doug Davis, Saunders College Publishing, Orlando, FL, 1994
- Wikipedia:Coulomb's Law
- Wikipedia:Dielectric constant
- GCSE Science/Static Electricity
- GCSE Science/Advanced static electricity topics

Next: Voltage, Current, and Power
Return to: Electronics Outline

Basic Concepts

What is Electronics?

Electronics is the study of flow of electrons in various materials or space subjected to various conditions. In the past, electronics dealt with the study of Vacuum Tubes or Thermionic valves, today it mainly deals with flow of electrons in semiconductors. However, despite these technological differences, the main focus of electronics remains the controlled flow of electrons through a medium. By controlling the flow of electrons, we can make them perform special tasks, such as power an induction motor or heat a resistive coil.

Plumbing Analogy A simple way to understand electrical circuits is to think of them as pipes. Let's say you have a simple circuit with a voltage source and a resistor between the positive and negative terminals on the source. When the circuit is powered, electrons will move from the negative terminal, through the resistor, and into the positive terminal. The resistor is basically a path of conduction that resists the movement of electrons. This circuit could also be represented as a plumbing network. In the plumbing network, the resistor would be equivalent to a section of pipe, where the water is forced to move around several barriers to pass through, effectively slowing its flow. If the pipe is level, no water will flow in an organized fashion, since the pressure is equal throughout the pipe. However, if we tilt the pipe to a vertical position (similar to turning on a voltage source), a pressure difference is created (similar to a voltage difference) and the water begins flowing through the pipe. This flow of water is similar to the flow of electrons in a circuit.

Electricity

To understand electronics, you need to understand electricity and what it is. Basically, electricity is the flow of electrons due to a difference in electrical charge between two points. This difference in charge is created due to a difference in electron density. If you have a point where the electron density is higher than the electron density at another point, the electrons in the area of higher density will want to balance the charge by migrating towards the area with lower density. This migration is referred to as electrical current. Thus, flow in an electrical circuit is induced by putting more electrons on one side of the circuit than the other, forcing them to move through the circuit to balance the charge density.

Electric Charge

In normal conditions all matter has a neutral or has a zero net charge. When an object receives an electron the object becomes negatively charged. When an object gives up an electron the object becomes positively charged. Each charge possesses electric field lines and charge quantities. A positive charge possesses charge quantities of +Q and has electric field lines going outward. A negative charge possesses charge quantities of -Q and has electric field lines going inward. In general, like charges will oppose each other and opposite charges will attract each other.

Coulomb's Law

The force of attraction between two charges can be calculated by Coulomb's Law. Below would be the calculation between a positive and negative charge.

Ampere's Law

The electric force, F, on a charge, Q, within an electric field, E, are related by Ampere's Law. On an atomic basis, this is the force that gives rise to current.

Lorentz's Law

When a charge in motion passes through a magnetic field. The magnetic field will push a positive charge upward and negative charge downward in the direction perpendicular to the initial direction traveled. The magnetic force on the charge is calculated by Lorennt's Law

ElectroMagnetic Force

The sum of Ampere's Force and Lorentz's Force exert on a charge is called EletroMagnetic Force

Electricity and Matter

All matter interacts with Electricity, and are divided into three categories: Conductors, Semi Conductors, and Non Conductors.

Conductor

Matter that conducts Electricity easily. Metals like Zinc (Zn) and Copper (Cu) conduct electricity very easily. Therefore, they are used to make Conductors.

Non-Conductor

Matter that does not conduct Electricity at all. Non-Metals like Wood and Rubber do not conduct electricity so easily. Therefore, they are used to make Non-Conductors.

Semi Conductor

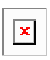
Matter that conducts electricity in a manner between that of Conductors and Non-Conductors. For example, Silicon (Si) and Germanium (Ge) conduct electricity better than non-conductors but worse than conductors. Therefore, they are used to make Semi Conductors.

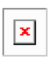
Electricity and Conductors

Normally, all conductors have a zero net charge . If there is an electric force that exerts a pressure on the charges in the conductor to force charges to move in a straight line result in a stream of electric charge moving in a straight line

Voltage

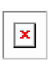
The pressure the electric force exert on the charges is called *voltage* denoted as V measured in Volt (V) and defined as the *ratio of Work Done on Charge*





Current

The moving of straight lines of electric charges in the conductor is called *current* denoted as I measured in Ampere (A) and defined as *Charge flow through an area in a unit of time*



Conductance

Conductance is defined as *the ratio of current over voltage* denoted as Y measured in mho

Resistance

Resistance is defined as *the ratio of voltage over current* denoted as R measured in Ohm

Generally, resistance of any conductor is found to increase with increasing temperature

For Conductor

$R = Ro(1 + nT)$

For Semi Conductor

$R = Ro\ e^{nT}$

When a conductor conducts electricity, it dissipates heat energy into the surrounding . This results in a loss of electric energy transmitted . *If the electric supply energy is P_V and the electric loss energy is P_R Then the electric energy delivered:*

$P = P_V - P_R$

Black Body Radiation

Further experience with conductors that conduct electricity . It is observed that all conductors that conduct electricity exhibit

1. Change in Temperature
2. Release Radiant Heat Energy into the surrounding

Experiment

Connect a conductor with an electric source in a closed loop . Plot the value I at different f to have a I - f diagram

Observation

for f<fo

Current increasing with increasing f .

Radiant heat is a wave travels at velocity $v = \lambda f$ carries energy $E = m v^2$.

for f=fo,

Current stops increasing .

Radiant heat is a wave travels at velocity v = c (speed of Light) carries energy E = hfo .

for f>fo,

Current remains at the value of current at fo .

Radiant heat is a wave travels at velocity v = c (speed of Light) carries energy E = h nfo

Conclusion

1. All conductor that conducts Electricity has a threshold frequency fo
2. The Radiant Heat Energy is a Light Wave of dual Wave Particle characteristic. Sometimes it behaves like Particle, sometimes it behaves like Wave
3. At Frequency f > fo . The energy of the Light is quantized . it can only have the value of multiple integer of fo . E = hf = h nfo

Cells

Cells

- Cell: Two materials with a voltage difference between them. This causes current to flow, which does work. Electrons travel from the cathode, do some work, and are absorbed by the anode.

- Anode: Destination of electrons.
- Cathode: Source of electrons.
- ions: An atom with an imbalance of electrons.

- cell operation: The cell runs and electrons are depleted at the cathode and accumulate at the anode. This creates a reverse voltage which stops the flow of electrons.

- irreversible: At some point the voltage difference reactions between the cathode and anode will decrease to a point that the cell in unusable. At this point, in an irreversible cell, the voltage difference is irreplaceably lost, and the cell is of no further use.
- reversible: Able to run the cell backwards.
- rechargeable: In a rechargeable cell, when the voltage difference between the cathode and anode decreases, the cell can be recharged, thereby increasing the voltage difference to a suitable level to allow continued use.

humid air will discharge cells.

cells are usually made of toxic or corrosive substances, for example lead and sulphuric acid. Such substances have been known to explode.

- Electronegativity [1]

What is the relationship between voltage and electronegativity?

Electronegativity is a concept in chemistry used to measure and predict the relative likelihood of a chemical reaction causing electrons to shift from one chemical to another resulting in ions and molecular bonds. A battery cell operates by allowing two chemicals to react and supply ions to the anode and cathode. When the supply of a reactant is consumed, the battery is dead. It no longer produces different electrical potential at the anode and cathode driven by the chemical reaction.

Voltage is the electrical potential of a point due to surrounding measurable electric charge distributions and points as calculated by application Coulomb's Law. Voltage difference between two points connected by a conductor results in electron flow.

Resistors

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Resistor

A resistor is a block or material that limits the flow of current. The greater the resistance, the lower the current will be, assuming the same voltage imposed on the resistor. The hydraulic analogy of a resistor would be the pipe with water flowing through it. The wider the diameter of a pipe, the higher the water flow through the pipe, assuming the same pressure difference on the terminals of a pipe.

Resistor's Symbol

Resistors have two leads (points of contact) to which the resistor can be connected to an electrical circuit. A symbol for a resistor used in electrical circuit diagrams is shown below.

The endpoints at the left and right sides of the symbol indicate the points of contact for the resistor. The ratio of the voltage to current will always be positive, since a higher voltage on one side of a resistor is a positive voltage, and a current will flow from the positive side to the negative side, resulting in a positive current. If the voltage is reversed, the current is reversed, leading again to a positive resistance.

Resistance

Resistance is a characteristic of Resistor indicates the measurement of current opposition . Resistance has a symbol R measured in Ohm (Ω) . The ratio of voltage to current is referred to as Ohm's Law, and is one of the most basic laws that govern electronics.

An ohm is the amount of resistance which passes one ampere of current when a one volt potential is placed across it. (The ohm is actually defined as the resistance which dissipates one watt of power when one ampere of current is passed through it.)

Resistance can vary from very small to very large. A superconductor has zero resistance, while something like the input to an op-amp can have a resistance near 10^{12} Ω, and even higher resistances are possible.

Resistance and Temperature

For most materials, resistance increases with increasing Temperature

For Conductor .

For Semi Conductor .

Resistance and Electric Power Loss

Resistance converts Electrical Energy into Heat this causes Electric Energy Loss.

NOTE : Resistors which dissipate large amounts of power are cooled so that they are not destroyed, typically with finned heatsinks.

If Electric Energy Supply is P_v and Electric Energy Loss is P_r Then, Electric Energy Delivered is

The ratio of Electric Energy Delivered over Electric Energy Supplied indicates the Efficiency of Electric Power Supply

Resistor's Labeling (See also Identification)

A manufactured resistor is usually labeled with the nominal value (value to be manufactured to) and sometimes a tolerance. Rectangular resistors will usually contain numbers that indicate a resistance and a multiplier. If there are three or four numbers on the resistor, the first numbers are a resistance value, and the last number refers to the number of zeroes in the multiplier. If there is an R in the value, the R takes the place of the decimal point.

Examples

2003 means $200 \times 10^3 = 200\text{k}\Omega$

600 means $60 \times 10^0 = 60\Omega$

2R5 means 2.5Ω

R01 means 0.01Ω

Cylindrical resistors (axial) usually have colored bands that indicate a number and a multiplier. Resistance bands are next to each other, with a tolerance band slightly farther away from the resistance bands. Starting from the resistance band side of the resistor, each colour represents a number in the same fashion as the number system shown above.

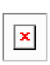
Colour System

Black	Brown	Red	Orange	Yellow	Green	Blue	Violet	Grey	White
0	1	2	3	4	5	6	7	8	9

Clue : B.B.ROY of Great Britain was a Very Good Worker. **Additional Colours**: A gold band in the multiplier position means 0.1, but means a 5% tolerance in the tolerance position. A silver band in the multiplier position means 0.01, but means 10% in the tolerance position.

Resistor's Construction

The resistance *R* of a component is dependent on its physical dimension and can be calculated using:



where

ϱ is the electrical resistivity (resistance to electricity) of the material,

L is the length of the material

A is the cross-sectional area of the material.

If you increase ϱ or L you increase the resistance of the material, but if you increase A you decrease the resistance of the material.

Resistivity of the Material

Every material has its own resistivity, depending on its physical makeup. Most metals are conductors and have very low resistivity; whereas, insulators such as rubber, wood, and air all have very high resistivity. The inverse of resistivity is conductivity, which is measured in units of Siemens/metre (S/m) or, equivalently. mhos/metre.

In the following chart, it is not immediately obvious how the unit ohm-meter is selected. Considering a solid block of the material to be tested, one can readily see that the resistance of the block will decrease as its cross-sectional area increases (thus widening the conceptual "pipe"), and will increase as the length of the block increases (lengthening the "pipe"). Given a fixed length, the resistance will increase as the cross-sectional area decreases; the resistance, multiplied by the area, will be a constant. If the cross-sectional area is held constant, as the length is increased, the resistance increases in proportion, so the resistance divided by the length is similarly a constant. Thus the bulk resistance of a material is typically measured in ohm meters squared per meter, which simplifies to ohm - meter (Ω-m).

Conductors Ω-m (Ohm-meter)	
Semiconductors	
Insulators	
Silver	1.59×10^{-8}
Copper	1.72×10^{-8}
Gold	2.44×10^{-8}
Aluminum	2.83×10^{-8}
Tungsten	5.6×10^{-8}
Iron	10×10^{-8}
Platinum	11×10^{-8}
Lead	22×10^{-8}
Nichrome	1.50×10^{-6} (A nickel-chromium alloy commonly used in heating elements)
Graphite	$\sim10^{-6}$
Carbon	3.5×10^{-5}
Pure Germanium	0.6
Pure Silicon	640
Common purified water	$\sim10^{3}$
Ultra-pure water	$\sim10^{5}$
Pure Gallium Arsenide	$\sim10^{6}$
Diamond	$\sim10^{10}$

Conductors Ω-m (Ohm-meter)	
Semiconductors	
Insulators	
Glass	10^{10} to 10^{14}
Mica	9×10^{13}
Rubber	10^{13} to 10^{16}
Organic polymers	$\sim10^{14}$
Sulfur	$\sim10^{15}$
Quartz (fused)	5 to 75×10^{16}
Air	very high

Silver, copper, gold, and aluminum are popular materials for wires, due to low resistivity. Silicon and germanium are used as semiconductors. Glass, rubber, quartz crystal, and air are popular dielectrics, due to high resistivity.

Many materials, such as air, have a non-linear resistance curve. Normal undisturbed air has a high resistance, but air with a high enough voltage applied will become ionized and conduct very easily.

The resistivity of a material also depends on its temperature. Normally, the hotter an object is, the more resistance it has. At high temperatures, the resistance is proportional to the absolute temperature. At low temperatures, the formula is more complicated, and what counts as a high or low temperature depends on what the resistor is made from. In some materials the resistivity drops to zero below a certain temperature. This is known as superconductivity, and has many useful applications.

(Some materials, such as silicon, have less resistance at higher temperatures.)

For all resistors, the *change* in resistance for a *small* increase in temperature is *directly proportional* to the *change* in temperature.

Current passing through a resistor will warm it up. Many components have heat sinks to dissipate that heat. The heatsink keeps the component from melting or setting something on fire.

Length

The length of an object is directly proportional to its resistance. As shown in the diagram below, 1 unit cubed of material has 1 ohm of resistance. However, when 4 units are stacked lengthwise and a connection is made to the front and back sides respectively, the total resistance is 4 ohms. This is because the length of the unit is 4, whereas the cross-sectional area remains 1. However, if you were to make connections on the sides, the exact opposite would be true: the cross-sectional area would be 4 and the length 1, resulting in 0.25 ohms total resistance.

Cross-Sectional Area

Increasing area is the same as having resistors in parallel, so as you increase the area you add more paths for current to take.

The resistance of a material is inversely proportional to its cross-sectional area. This is shown in the diagram below, where 1 unit cubed has one ohm of resistance. However, if 4 units cubed are stacked on top of each other in the fashion such that there is 4 units squared of cross-sectional area, and the electrical connections are made to the front and back such that the connections are on the largest sides, the resultant resistance would be 0.25 ohms.

Additional note: There are two reasons why a small cross-sectional area tends to raise resistance. One is that the electrons, all having the same negative charge, repel each other. Thus there is resistance to many being forced into a small space. The other reason is that they collide, causing "scattering," and therefore they are diverted from their original directions. (More discussion is on page 27 of "Industrial Electronics," by D. J. Shanefield, Noyes Publications, Boston, 2001.)

Example

For instance, if you wanted to calculate the resistance of a 1 cm high, 1 cm wide, 5 cm deep block of copper, as shown in the diagram below:

You would first need to decide how it's oriented. Suppose you want to use it from front to back (lengthwise), like a piece of wire, with electrical contacts on the front and rear faces. Next you need to find the length, L. As shown, it is 5 cm long (0.05 m). Then, we look up the resistivity of copper on the table, 1.6×10^{-8} Ω-meters. Lastly, we calculate the cross-sectional area of the conductor, which is 1 cm × 1 cm = 1 cm^2 (0.0001 m^2). Then, we put it all in the formula, converting cm to m:

units m^2 cancel:

Which, after evaluating, gives you a final value of 8.0×10^{-6} Ω, or 8 microohms, a very small resistance. The method shown above included the units to demonstrate how the units cancel out, but the calculation will work as long as you use consistent units.

> Internet Hint: Google calculator can do calculations like this for you, automatically converting units. This example can be calculated with this link: [2]

Properties of the material

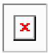
- **Wirewound**: Used for power resistors, since the power per volume ratio is highest. These usually have the lowest noise.
- **Carbon Film**: These are easy to produce, but usually have lots of noise because of the properties of the material.

- **Metal Film**: These resistors have thermal and voltage noise attributes that are between carbon and wirewound.

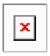
- **Ceramic**: Useful for high frequency applications.

Resistor Connection

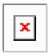
Resistors in Series



Resistors in series are equivalent to having one long resistor. If the properties of two resistors are equivalent, except the length, the final resistance will be the sum of the two construction methods:

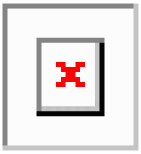


This means that the resistors add when in series.

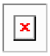


- Christmas tree lights are usually connected in series, with the unfortunate effect that if one light blows, the others will all go out (This happens because the circuit is not complete, if a circuit is not complete then the current cannot flow, hence the light bulbs all go out). However, most modern Christmas light strings have built in shunt resistors in parallel to the bulb, so that current will flow past the blown light bulb.

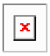
Resistors in Parallel



In a parallel circuit, current is divided among multiple paths. This means that two resistors in parallel have a lower equivalent resistance than either of the parallel resistors, since both resistors allow current to pass. Two resistors in parallel will be equivalent to a resistor that is twice as wide:

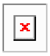


Since conductances (the inverse of resistance) add in parallel, you get the following equation:

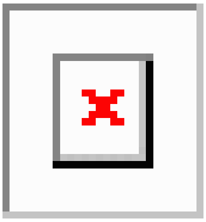


For example, two 4 Ω resistors in parallel have an equivalent resistance of only 2 Ω.

To simplify mathematical equations, resistances in parallel can be represented with two vertical lines "||" (as in geometry). For two resistors the parallel formula simplifies to:



Combinations of series and parallel



Resistors in parallel are evaluated as if in a mathematical set of "parentheses." The most basic group of resistors in parallel is evaluated first, then the group in series with the new equivalent resistor, then the next group of resistors in parallel, and so on. For example, the above portion would be evaluated as follows:

Resistor variations

- **Variable Resistor** or **Potentiometer**

Variable resistors are tunable, meaning you can turn a dial or slide a contact and change the resistance. They are used as knobs to control the volume of a stereo, or as a dimmer for a lamp. The term Potentiometer is often abbreviated as 'pot'. It is constructed like a resistor, but has a sliding tap contact. Potentiometers are used as Voltage Dividers. It is rare to find a variable resistor with only two leads. Most are potentiometers with three leads, even if one is not connected to anything.

- **Rheostat**

A variation of the potentiostat with a high current rating, which is used to control the amount of power going through a load, such as a motor.

- **Thermistor**

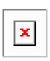
Temperature-sensitive resistor, in which the resistance decreases as the temperature rises. They are used in fire alarms, so if things get too hot the current rises and trips a switch that sounds an alarm.

- **LDR** (Light Dependent Resistor) or **Photoresistor**

A resistor which changes values depending on the amount of light shining on its surface. The resistance decreases as the amount of light increases. They are used in street lamps, so when it gets dark the current decreases and turns on the street lamp.

Applications

- **Voltage division / Attenuation**: Sometimes a voltage will be too large to measure, so a means to linearly reduce the voltage is required. Placing two resistors in series to ground will provide a point in the middle to tap. Resistor R_A is placed between the input voltage and the output node, and the resistor R_B is placed between the output node and ground. This creates a voltage divider to lessen the output voltage. Typically, the resistors are near the value of ~10kΩ. The Thevenin model of the circuit gives an output resistance $R_{OUT} = R_A || R_B$. A larger output resistance will more likely be affected by the input resistance of the measuring circuit (this is a desired effect in the transistor biasing circuits). Placement of the voltage divider should be close to the measuring circuit, to minimize noise (in this arrangement, it will be also lessened Rb/(Ra + Rb) times). The output voltage of the voltage divider is



- **Pull-up / Pull-down**: If there is nothing to drive a signal node, the node will be left "floating" (for example, such a situation occurs at the trigger input of a car alarm system when the driver has switched off the internal lamp). This may lead to unintended values being measured, or causing side-effects when the voltage is propagated down the remainder of the circuit. To prevent this, a relatively high value resistor (usually ~10kΩ to ~1MΩ) is placed between the node and ground (pull-down) or a high voltage (pull-up) to bring the voltage of the "floating" node near to the voltage it is being pulled. A resistive voltage divider is another example where the upper resistor "pulls" the output point up toward the input voltage while the lower resistor "pulls" the output point toward the ground. This idea is evolved in the circuit of a resistive voltage summer (for example, the resistors R_1 and R_2 of an op-amp inverting amplifier) supplied by two voltages (V_{IN} and $-V_{OUT}$) having opposite polarities. The two voltage sources "pull" the output point in opposite directions; as a result, if $R_2/R_1 = -V_{OUT}/V_{IN}$, the point becomes a virtual ground. Placement of a pull-up or pull-down resistor does not have a significant effect on the performance of the circuit, if they have high resistances.

- **Current limiting / Isolation**: In order to protect circuits from conditions that may cause too much current in a device, a current limiting resistor is inserted in the middle of the circuit. A digital input to a microcontroller may benefit from a current limiting resistor. The inputs to modern microcontrollers have protection circuitry built in that will protect the input from an overvoltage condition, provided that the current is small enough. For instance, a common microcontroller will be capable of withstanding 20mA. If there are 12V nets on a circuit board, or in a system, the digital input will benefit from a 350Ω resistor (refer to calculation below). Usually a slightly larger resistance is used in practice, but too large of a resistor will cause noise, and may prevent the input from being able to read the voltage. It is good practice to place the resistor as close as possible to the microcontroller input, so that an accidental short on the board will mean that the microcontroller input is likely still protected.

- **Line termination / Impedance matching**: The properties of an electric wave propagating through a conductor (such as a wire) create a reflection, which can be viewed as unwanted noise. A reflection can be eliminated by maximizing the power transfer between the conductor and the termination resistor. By matching the resistance (more importantly the impedance), the wave will not cause a reflection. The voltage of the echo V_r is calculated below in reference to the original signal V_o as a function of the conductor impedance Z_C and the terminator impedance Z_T. As the name implies, the termination resistor goes at the end of the conductor.

- **Current sensing**: Measurement of a current cannot be done directly. There are three major ways to measure a current: a resistor, a hall sensor, and an inductor. The hall sensor and inductor use a property of the magnetic field to sense the current through a nearby conductor. According to Ohm's law, if a current I flows through a resistor R, a voltage V = R.I appears across the resistor. Therefore, the resistor can act as a passive current-to-voltage converter. In this arrangement, the resistor should have a very low value (sometimes on the order of ~0.01Ω), so it does not affect the current flow or heat up; however, a smaller value has a lower voltage to read, which means more noise may be introduced. This contradiction is solved in the circuit of an active current-to-voltage converter where the resistor may have a significant resistance as an op-amp compensates the "undesired" voltage drop across it (unfortunately, this remedy may be applied only in low-current measurements). The current sense resistor should be placed as close as possible to where the measurement occurs, in order not to disturb the circuit.

- **Filtering**: Filtering is discussed later, after an introduction to capacitors and inductors. Filters are best placed close to where measurement takes place.

Specifications

Resistors are available as pre-fabricated, real-world components. The behavior of such components deviates from an ideal resistor in certain ways. Therefore, real-world resistors are not only specified by their resistance, but also by other parameters. In order to select a manufactured resistance, the entire range of specifications should be considered. Usually, exact values do not need to be known, but ranges should be determined.

Nominal Resistance

The nominal resistance is the resistance that can be expected when ordering a resistor. Finding a range for the resistance is necessary, especially when operating on signals. Resistors do not come in all of the values that will be necessary. Sometimes resistor values can be manipulated by shaving off parts of a resistor (in industrial environments this is sometimes done with a LASER to adjust a circuit), or by combining several resistors in series and parallel.

Available resistor values typically come with a resistance value from a so called resistor series. Resistor series are sets of standard, predefined resistance values. The values are actually made up from a geometric sequence within each decade. In every decade there are supposed to be

resistance values, with a constant step factor. The standard resistor values within a decade are derived by using the step factor

rounded to a two digit precision. Resistor series are named E

, according to the used value of

in the above formula.

n Values/Decade	Step factor i	Series
6	1.47	E6
12	1.21	E12
24	1.10	E24
48	1.05	E48

For example, in the E12 series for

, the resistance steps in a decade are, after rounding the following 12 values:

```
1.00, 1.20, 1.50, 1.80, 2.20, 2.70,
3.30, 3.90, 4.70, 5.60, 6.80, and 8.20
```

and actually available resistors from the E12 series are for example resistors with a nominal value of 120Ω or 4.7kΩ.

Tolerances

A manufactured resistor has a certain tolerance to which the resistance may differ from the nominal value. For example, a 2kΩ resistor may have a tolerance of ±5%, leaving a resistor with a value between 1.9kΩ and 2.1kΩ (i.e. 2kΩ±100Ω). The tolerance must be accounted for when designing circuits. A circuit with an absolute voltage of 5V±0.0V in a voltage divider network with two resistors of 2kΩ±5% will have a resultant voltage of 5V±10% (i.e. 5V±0.1V). The final resistor tolerances are found by taking the derivative of the resistor values, and plugging the absolute deviations into the resulting equation.

The above mentioned E-series which are used to provide standardized nominal resistance values, are also coupled to standardized nominal tolerances. The fewer steps within a decade there are, the larger the allowed tolerance of a resistor from such a series is. More precises resistors, outside of the mentioned E-series are also available, e.g. for high-precision measurement equipment. Common tolerances, colors and key characters used to identify them are for example:

```
 Series  Values/Decade  Tolerance  Color Code  Character Code
--------------------------------------------------------------
   E6         6          ±20%       [none]         [none]
   E12       12          ±10%       silver           K
   E24       24           ±5%       gold             J
   E48       48           ±2%       red              G
    -         -           ±1%       brown            F
    -         -           ±0.5%       -              D
    -         -           ±0.25%      -              C
    -         -           ±0.1%       -              B
```

Resistor manufacturers can benefit from this standardization. They manufacture resistors first, and afterwards they measure them. If a resistor does not meet the nominal value within the defined tolerance of one E-series, it might still fit into a lower series, and doesn't have to be thrown away, but can be sold as being compliant to that lower E-series standard. Although typically at a lower price.

Series: Resistors that combine in series add the nominal tolerances together.

Derivation:

Example: For two resistors in series R_A = 1.5kΩ±130Ω and R_B = 500Ω±25Ω, the tolerance is 130Ω + 25Ω, resulting in a final resistor value R_T = 2kΩ±155Ω.

Parallel: Resistors that combine in parallel have a combined tolerance that is slightly more complex.

Derivation:

Example: For two resistors in parallel R_A = 1.5kΩ±130Ω and R_B = 500Ω±25Ω.

Power Rating

Because the purpose of a resistor is to dissipate power in the form of heat, the resistor has a rating (in watts) at which the resistor can continue to dissipate before the temperature overwhelms the resistor and causes it to overheat. When a resistor overheats, the material begins to melt away, which will cause the resistance to increase (usually), until the resistor breaks.

Operating Temperature

Related to power rating, the operating temperature is the temperature that the resistor can continue to operate before being destroyed.

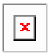
Maximum Voltage

In order to avoid sparkovers or material breakdown a certain maximum voltage over a resistor must not be exceeded. The maximum voltage is part of a resistor's specification, and typically a function of the resistor's physical length, distance of the leads, material and coating.

For example, a resistor with a maximum operating voltage of 1kV can have a length in the area of 2", while a 0.3" resistor can operate under up to several tens of volts, probably up to a hundred volts. When working with dangerous voltages it is essential to check the actual specification of a resistor, instead of only trusting it because of the length.

Temperature Coefficient

This parameter refers to the constant in which the resistance changes per degree Celsius (units in C^{-1}). The change in temperature is not linear over the entire range of temperatures, but can usually be thought of as linear around a certain range (usually around room temperature). However, the resistance should be characterized over a large range if the resistor is to be used as a thermistor in those ranges. The simplified linearized formula for the affect on temperature to a resistor is expressed in an equation:



Capacity and Inductance

Real world resistors not only show the physical property of resistance, but also have a certain capacity and inductance. These properties start to become important, if a resistor is used in some high frequency circuitry. Wire wound resistors, for example, show an inductance which typically make them unusable above 1kHz.

Packaging

Resistors can be packaged in any way possible, but are divided into surface mount, through hole, soldering tag and a few more forms. Surface mount is connected to the same side that the resistor is on. Through hole resistors have leads (wires) that typically go through the circuit board and are soldered to the board on the side opposite the resistor, hence the name. Resistors with leads are also used in point-to-point circuits without circuit boards. Soldering tag resistors have lugs to solder wires or high current connectors onto.

Usual packages for surface mount resistors are rectangular, referenced by a length and a width in mils (thousands of an inch). For instance, an 0805 resistor is a rectangle with length .08" x .05", with contacts (metal that connects to the resistor) on either side. Typical through hole resistors are cylindrical, referenced either by the length (such as 0.300") or by a typical power rating that is common to the length (a 1/4W resistor is typically 0.300"). This length does not include the length of the leads.

Related Wikimedia resources

Wikibooks

- Circuit Idea: Passive voltage-to-current converter shows how the bare resistor can act as a simple voltage-to-current converter.

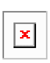
Wikipedia

- Voltage-to-current converter builds consecutively the passive and active versions of the voltage-to-current converter.
- Current-to-voltage converter is dedicated to the passive and active versions of the inverse current-to-voltage converter.

Capacitors

Electronics | Foreword | Basic Electronics | Complex Electronics | Electricity | Machines | History of Electronics | Appendix | edit

Capacitors



Model of a capacitor

A capacitor (historically known as a "condenser") is a device that stores energy in an electric field, by accumulating an internal imbalance of electric charge. It is made of two conductors separated by a dielectric (insulator).

Using the same analogy of water flowing through a pipe, a capacitor can be thought of as a tank, in which the charge can be thought of as a volume of water in the tank. The tank can "charge" and "discharge" in the same manner as a capacitor does to an electric charge. A mechanical analogy is that of a spring. The spring holds a charge when it is pulled back.

When voltage exists one end of the capacitor is getting drained and the other end is getting filled with charge.This is known as charging. Charging creates a charge imbalance between the two plates and creates a reverse voltage that stops the capacitor from charging. As a result, when capacitors are first connected to voltage, charge flows only to stop as the capacitor becomes charged. When a capacitor is charged, current stops flowing and it becomes an open circuit. It is as if the capacitor gained infinite resistance.

You can also think of a capacitor as a fictional battery in series with a fictional resistance. Starting the charging procedure with the capacitor completely discharged, the applied voltage is not counteracted by the fictional battery, because the fictional battery still has zero voltage, and therefore the charging current is at its maximum. As the charging continues, the voltage of the fictional battery increases, and counteracts the applied voltage, so that the charging current decreases as the fictional battery's voltage increases. Finally the fictional battery's voltage equals the applied voltage, so that no current can flow into, nor out of, the capacitor.

Just as the capacitor charges it can be discharged. Think of the capacitor being a fictional battery that supplies at first a maximum current to the "load", but as the discharging continues the voltage of the fictional battery keeps decreasing, and therefore the discharge current also decreases. Finally the voltage of the fictional battery is zero, and therefore the discharge current also is then zero.

This is not the same as dielectric breakdown where the insulator between the capacitor plates breaks down and discharges the capacitor. That only happens at large voltages and the capacitor is usually destroyed in the process. A spectacular example of dielectric breakdown occurs when the two plates of the capacitor are brought into contact. This causes all the charge that has accumulated on both plates to be discharged at once. Such a system is popular for powering tasers which need lots of energy in a very brief period of time.

Capacitance

The capacitance of a capacitor is a ratio of the amount of charge that will be present in the capacitor when a given potential (voltage) exists between its leads. The unit of capacitance is the farad which is equal to one coulomb per volt. This is a very large capacitance for most practical purposes; typical capacitors have values on the order of microfarads or smaller.

Where C is the capacitance in farads, V is the potential in volts, and Q is the charge measured in coulombs. Solving this equation for the potential gives:

Capacitor & Direct Current Voltage (DC)

Charge Building

When a Capacitor is connected with electricity source V . Charge will build up on each plates of capacitor of the same amount of charge but different in polarity . This process is called Capacitor Charging

Storing Charge

When both plates are charged up to voltage V then there is no difference in voltage between capacitor's plates and electricity source therefore no current flow in the circuit. This is called Storing Charge

Charge discharge

When the capacitor is connected to ground, current will flow from capacitor to ground until the voltage on capacitor's plates are equal to zero.

Therefore, a Capacitor is a device that can Build up Charge , Store Charge and Release Charge

Capacitor & Alternating Current Voltage (AC)

Voltage

Current

Reactance

Reactance is defined as the ratio of Voltage over Current

Impedance

Impedance is defined as the sum of Capacitor's Resistance and Reactance

Angle of Difference between Voltage and Current

For Lossless Capacitor

Current will lead Voltage an angle 90 degree

For Lossy Capacitor

Current will lead Voltage an angle θ degree where

Tan θ =

Changing the value of R and C will change the value of Phase Angle, Angular Frequency, Frequency and Time

Time Constant

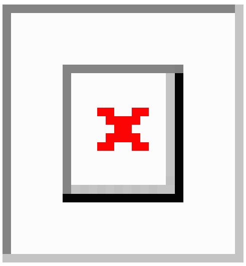
Capacitor Labeling

Capacitors are labelled in several different ways.

Ceramic Disc

Sometimes labeled implicitly, usually labeled with number scheme (223 = 22 000 pF, where 3 represents the number of "0" for instance) The letters "mfd" are often used in place of "µF".

Ceramic Dipped



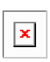
Ceramic-dipped capacitors.

These usually use the number code. In the above example, the smallest one says "104". This means 10 0000 pF = 100,000 pF. *M* is a tolerance. The middle one is labeled 393. This means 39 000 pF. The last is 223, meaning 22 000 pF. *K* is the tolerance. It also has a 100 V working voltage labeled. Colours on capacitor are an indication for capacitance. Red dipped caps are ___

Green dipped caps are ___

Mylar or polyester film?

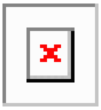
Resin-potted mylar/polyester



"Box-style" capacitors.

These are usually labeled explicitly, as there is lots of surface area to write on. This one is 4700 pF, 250 V, 5 kV test. The frequency f_0 = 21 MHz is the frequency at which it stops behaving like a capacitor, and more like an inductor.

Electrolytic

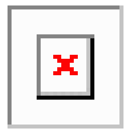


Axial 1000 µF capacitor with a maximum voltage rating of 35 V (black), and radial 10 µF capacitor with a maximum voltage rating of 160 V (blue).

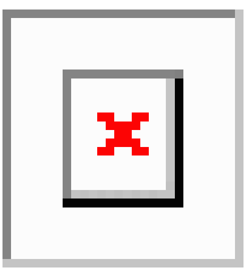
Usually electrolytic caps are labeled explicitly, making identification easy.

Electrolytics are available in axial and radial-leaded packages. In axial-leaded parts, the negative terminal is indicated by a minus sign printed on the package, or by a shorter lead.

Radial-lead parts often uses color code like resistors. The polarity is usually indicated by arrows on a stripe pointing to the negative terminal.



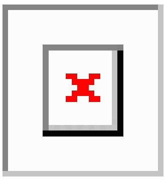
This image shows a pair of radial electrolytic capacitors with leads. The industry standard, as shown, is that the positive lead is longer than the negative lead.



Aluminum electrolytic capacitors of the "snap-in" type. The leads are angled so that they may be "snapped" into a printed circuit board with holes of the correct spacing.

Warning: You should never connect an electrolytic capacitor in such a way that a negative voltage is applied across the terminals from positive to negative. It will explode.

Tantalum

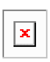


Radial tantalum capacitor.

Tantalum capacitors have high capacitance and low ESR, but low operating voltages. When tantalum capacitors fail, it tends to be "spectacular," they essentially blow up.

Construction

The capacitance of a *parallel-plate* capacitor constructed of two identical plane electrodes of area *A* at constant spacing *D* is approximately equal to the following:



where

C is the capacitance in farads

ε_0 is the Permittivity of Space,

ε_r is the Dielectric Constant

A is the area of the capacitor plates, and *D* is the distance between them.

A dielectric is the material between the two charged objects. Dielectrics are insulators. They impede the flow of charge in normal operation. Sometimes, when a too large voltage has been reached, charge starts flowing. This is called dielectric breakdown and **destroys the capacitor**. Beginners sometimes misunderstand this. Timing circuits do measure the rate at which a capacitor charges, but they measure a threshold voltage instead of allowing the voltage to build up until dielectric breakdown. (A device which *does* function this way is a spark gap.)

No charge should ever flow from one plate to the other. Although a current does flow through the capacitor, charges are not actually moving from one plate to the other. As charges are added to one plate, their electric field displaces like charges off of the other plate. This is called a *displacement current*.

Materials

Capacitors can be made either polarized or non-polarized. A polarized capacitor requires that the capacitor be hooked up such that the voltage is always biased in one direction. Hooking a polarized capacitor backwards will result in the capacitor exploding, sometimes releasing harmful fumes. Non-polarized capacitors can be biased in either direction without harm to the capacitor. Polarized and non-polarized capacitors have an upper limit of voltage, where the material will break down and the capacitor will no longer function. This can also cause fumes to be released depending on the type of material. Different materials and their properties.

Ceramic

These are normally low capacitance (between ~1pF to ~1μF). Ceramic capacitors have a very low inductance due to the shape. This means that the capacitance value continues into extremely high frequencies, making them perfect for RF applications. However, ceramic capacitors tend to vary their capacitance with temperature.

- - C0G or NP0 - Typical 4.7 pF to 0.047 μF, 5%. High tolerance and temperature performance. Larger and more expensive.

- X7R - Typical 3300 pF to 0.33 μF, 10%. Good for non-critical coupling, timing applications.
- Z5U - Typical 0.01 μF to 2.2 μF, 20%. Good for bypass, coupling applications. Low price and small size.

Polystyrene

Slightly larger than ceramic, but still has small values (usually in the picofarad range).

Polyester

from about 1 nF to 1 μF

Polypropylene

low-loss, high voltage, resistant to breakdown

Tantalum

These are polarized capacitors that are still small enough to be surface mount. Normally the dielectric breakdown voltage is rather low -- typically less than 20 volts -- so the capacitors are not suitable for high voltage applications. Tantalum capacitors have a stable capacitance across varying temperatures, but higher (worse) ESR than any other capacitor material except for electrolytic. Tantalum capacitors have the highest (best) energy density of any material.

Electrolytic

These are also polarized, are much larger than tantalums. The dielectric strength is much higher in these, and so is the capacitance. Capacitance values can range between 1μF and 1mF (sometimes up into the farad range). These are compact capacitors -- higher (best) energy density of any material other than tantalums. Electrolytic capacitors also very lossy -- at high frequencies they have the highest (worst) ESR of any capacitor material. They are useful for smoothing power supplies because of the high capacitance.

Air-gap

Aerogel

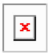
These capacitors are more compact than normal electrolytic capacitors, giving capacitance values in the farad range, but normally have an extremely low breakdown voltage.

Super capacitors 2500 F to 5000 F

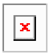
Capacitor Connection

Capacitors in Series

Capacitors in series are the same as increasing the distance between two capacitor plates. As well, it should be noted that placing two 100 V capacitors in series results in the same as having one capacitor with the total maximum voltage of 200 V. This, however, is not recommended to be done in practice. Especially with capacitors of different values. In a capacitor network in series, **all capacitors can have a different voltage over them**.

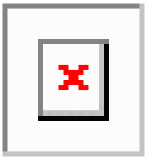


In a series configuration, the capacitance of all the capacitors combined is the reciprocal of the sum of the reciprocals of the capacitance of all the capacitors.

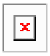


Capacitors in Parallel

Capacitors in parallel are the same as increasing the total surface area of the capacitors to create a larger capacitor with more capacitance. In a capacitor network in parallel, **all capacitors have the same voltage over them**.



In a parallel configuration, the capacitance of the capacitors in parallel is the sum of the capacitance of all the capacitors.



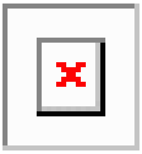
RC Circuit

Introduction

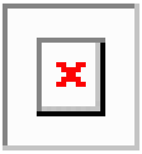
An **RC** circuit is short for 'Resistor-Capacitor' circuit. A capacitor takes a finite amount of time to discharge through a resistor, which varies with the values of the resistor and capacitor. A capacitor acts interestingly in an electronic circuit, practically speaking as a combination of a voltage source and a variable resistor.

Basics

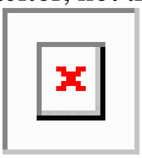
Below is a simple RC Circuit:



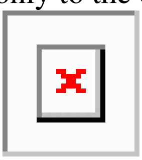
There is a capacitor in parallel with the resistor and current probe. The way the capacitor functions is by acting as a very low resistance **load** when the circuit is initially turned on. This is illustrated below:



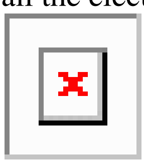
Initially, the capacitor has a very low resistance, almost 0. Since electricity takes the path of least resistance, almost all the electricity flows through the capacitor, not the resistor, as the resistor has considerably higher resistance.



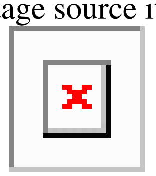
As a capacitor charges, its resistance increases as it gains more and more charge. As the resistance of the capacitor climbs, electricity begins to flow not only to the capacitor, but through the resistor as well:



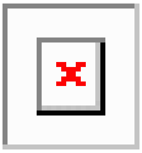
Once the capacitor's voltage equals that of the battery, meaning it is fully charged, it will not allow any current to pass through it. As a capacitor charges its resistance increases and becomes effectively infinite (open connection) and all the electricity flows through the resistor.



Once the voltage source is disconnected, however, the capacitor acts as a voltage source itself:



As time goes on, the capacitor's charge begins to drop, and so does its voltage. This means less current flowing through the resistor:



Once the capacitor is fully discharged, you are back to square one:

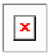
If one were to do this with a light and a capacitor connected to a battery, what you would see is the following:

1. Switch is closed. Light does not light up.
2. Light gradually becomes brighter and brighter...
3. Light is at full luminosity.
4. Switch is released. Light continues to shine.
5. Light begins to fade...
6. Light is off.

This is how a capacitor acts. However, what if you changed the values of R1? C1? The voltage of the battery? We will examine the mathematical relationship between the resistor, capacitor, and charging rate below.

The Time Constant

In order to find out how long it takes for a capacitor to fully charge or discharge, or how long it takes for the capacitor to reach a certain voltage, you must know a few things. First, you must know the starting and finishing voltages. Secondly, you must know the **time constant** of the circuit you have. Time constant is denoted by the Greek letter 'tau' or τ. The formula to calculate this time constant is:



Great, so what does this mean? The time constant is how long it takes for a capacitor to charge to 63% of its full charge. This time, in seconds, is found by multiplying the resistance in ohms and the capacitance in farads.

According to the formula above, there are two ways to lengthen the amount of time it takes to discharge. One would be to increase the resistance, and the other would be to increase the capacitance of the capacitor. This should make sense. It should be noted that the formula compounds, such that in the second time constant, it charges another 63%, based on the original 63%. This gives you about 86.5% charge in the second time constant. Below is a table.

Time Constant	Charge
1	63%
2	87%
3	95%
4	98%
5	99+%

For all practicality, by the 5th time constant it is considered that the capacitor is fully charged or discharged.

put some stuff in here about how discharging works the same way, and the function for voltage based on time

Where $i(t)$ is the current flowing through the capacitor as a function of time.

This equation is often used in another form. By differentiating with respect to time:

Substituting v/r for i(t) and integrating the above equation gives you an equation used to describe the charging and discharging characteristics of RC circuits. A charging characteristic curve exponentially increases from 0% (0 volts) and approaches 100% full (maximum voltage), similarly, a discharge curve starts at the theoretical 100% (maximum voltage) and exponentially falls back to 0% (0 volts).

Capacitor Specifications

When a capacitor is being discussed, it is referred to with certain "specifications" or characteristics. Capacitors are usually "specified" in the following manner-

- they are specified by type (tantalum, electrolytic, etc.)
- they are specified by package (axial, radial, as discussed above).
- they are specified by how to connect to them, their connection type (such as "snap in" or leaded, or threaded screw holes, or surface mount).
- they are specified by capacitance value, e.g. in microfarads (μF).
- they are specified by voltage rating (i.e., 30 V). This indicates the maximum voltage under which it is safe to use the referenced capacitor.
- some types, such as electrolytic capacitors, are specified by operating temperature (usually 80 or 120 °C), which reflects the maximum temperature that the capacitor can reach before failing. Note- common practice is to use capacitors well below their maximum operating voltage and temperature in order to ensure longevity.
- they can be specified by other parameters, including ESR or "equivalent series resistance" (explained above). Also, some capacitors can be specified by UL or other safety rating. A "X" type capacitor indicates that the capacitor meets certain standards one of which is that it is appropriate to be used with line-level voltages (such as 117 or 220 V) typically found from the wall outlet, as well as that it can withstand surges typically found in power distribution systems.

- they are specified in percentage accuracy, i.e., how much they are likely to deviate from their rated capacitance. Common ratings are + or - 20%.

Capacitor Variations

- **Variable Capacitor:**

Wikipedia has related information at ***Electrolytic capacitor***

Inductors

Electronics | Foreword | Basic Electronics | Complex Electronics | Electricity | Machines | History of Electronics | Appendix | edit

Inductor

An inductor is a passive electronic component dependent on frequency used to store electric energy in the form of a magnetic field. An inductor has the symbol

Inductance

Inductance is the characteristic of the Inductor to generates a magnetic field for a given current. Inductance has a letter symbol L and measured in units of Henry (H).

This section list formulas for inductances in specific situations. Beware that some of the equations are in Imperial units.

The permeability of free space, μ_0, is constant and is defined to be exactly equal to $4\pi\times10^{-7}$ H m^{-1}.

Basic inductance formula for a cylindrical coil

L = inductance / H

μ_r = relative permeability of core material

N = number of turns

A = area of cross-section of the coil / m^2

l = length of coil / m

The self-inductance of a straight, round wire in free space

L_{self} = self inductance / H

b = wire length /m

a = wire radius /m

= relative permeability of wire

If you make the assumption that *b* >> *a* and that the wire is nonmagnetic (

), then this equation can be approximated to

(for low frequencies)

(for high frequencies due to the skin effect)

L = inductance / H

b = wire length / m

a = wire radius / m

The inductance of a straight wire is usually so small that it is neglected in most practical problems. If the problem deals with very high frequencies (*f* > 20 GHz), the calculation may become necessary. For the rest of this book, we will assume that this self-inductance is negligible.

Inductance of a short air core cylindrical coil in terms of geometric parameters:

L = inductance in μH

r = outer radius of coil in inches

l = length of coil in inches

N = number of turns

Multilayer air core coil

L = inductance in µH

r = mean radius of coil in inches

l = physical length of coil winding in inches

N = number of turns

d = depth of coil in inches (i.e., outer radius minus inner radius)

Flat spiral air core coil

L = inductance / H

r = mean radius of coil / m

N = number of turns

d = depth of coil / m (i.e. outer radius minus inner radius)

Hence a spiral coil with 8 turns at a mean radius of 25 mm and a depth of 10 mm would have an inductance of 5.13µH.

Winding around a toroidal core (circular cross-section)

L = inductance / H

μ_r = relative permeability of core material

N = number of turns

r = radius of coil winding / m

D = overall diameter of toroid / m

Quality of good inductor

There are several important properties for an inductor that may need to be considered when choosing one for use in an electronic circuit. The following are the basic properties of a coil inductor. Other factors may be important for other kinds of inductor, but these are outside the scope of this article.

- Current carrying capacity is determined by wire thickness and resistivity.
- The quality factor, or Q-factor, describes the energy loss in an inductor due to imperfection in the manufacturing.
- The **inductance** of the coil is probably most important, as it is what makes the inductor useful. The inductance is the response of the inductor to a changing current.

The inductance is determined by several factors.

- Coil shape: short and squat is best
- Core material
- The number of turns in the coil. These must be in the same direction, or they will cancel out, and you will have a resistor.
- Coil diameter. The larger the diameter (core area) the less induction.

Coil's Characteristics

For a Coil that has the following dimension

Area enclosed by each turn of the coil is *A*

Length of the coil is 'l'

Number of turns in the coil is *N*

Permeability of the core is μ. μ is given by the permeability of free space, μ_0 multiplied by a factor, the relative permeability, μ_r

The current in the coil is 'i'

The magnetic flux density, *B*, inside the coil is given by:

We know that the flux linkage in the coil, λ, is given by;

Thus,

The flux linkage in an inductor is therefore proportional to the current, assuming that *A, N, l* and μ all stay constant. The constant of proportionality is given the name **inductance** (measured in Henries) and the symbol *L*:

Taking the derivative with respect to time, we get:

Since *L* is time-invariant in nearly all cases, we can write:

Now, Faraday's Law of Induction states that:

We call

the electromotive force (emf) of the coil, and this is opposite to the voltage *v* across the inductor, giving:

This means that the voltage across an inductor is equal to the rate of change of the current in the inductor multiplied by a factor, the inductance. note that for a constant current, the voltage is zero, and for an instantaneous change in current, the voltage is infinite (or rather, undefined). This applies only to ideal inductors which do not exist in the real world.

This equation implies that

- The voltage across an inductor is proportional to the derivative of the current through the inductor.
- In inductors, voltage leads current.
- Inductors have a high resistance to high frequencies, and a low resistance to low frequencies. This property allows their use in filtering signals.

An inductor works by opposing current change. Whenever an electron is accelerated, some of the energy that goes into "pushing" that electron goes into the electron's kinetic energy, but much of that energy is stored in the magnetic field. Later when that or some other electron is decelerated (or accelerated the opposite direction), energy is pulled back out of the magnetic field.

Inductor and Direct Current Voltage (DC)

When connect a Coil of several turns to an Electricity source in a closed loop . The current in the circuit set up a Magnetic Field that has the same properties like a Magnetic Field of a Magnet

B = L I

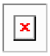
When the current is turned off , the Magnetic Field does not exist .

B = 0

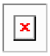
Conducting Coil is called ElectroMagnet

Inductor and Alternating Current Voltage (AC)

Inductor's Voltage



Inductor's Current



Reactance

Impedance

Angle Difference Between Voltage and Current

For Lossless Inductor

The angle difference between Voltage and Current is 90

For Lossy Inductor

Change the value of L and R_L will change the value of Angle of Difference , Angular Frequency, requenct and Time

Time Constant

Quality factor

Quality factor denoted as Q is defined as the ability to store energy to the sum total of all energy losses within the component

Inductor's Connection

Series Connection

Parallel Connection

See Also

- Networks
- Real Inductors
- Special Cases
- Transient Analysis

Other Components

Ideal voltage sources

An ideal voltage source is a fundamental electronics component that creates a constant voltage between two points regardless of whatever else is connected to it. Since it is ideal, some circuit configurations are not allowed, such as short circuits, which would create infinite current. (I = V / 0)

A water analogy would be a pump with pressure sensors on both sides. The *difference* in pressure between the in port and out port is constantly measured, regardless of the absolute pressure of each side, and the pump speed is adjusted so that the pressure difference stays constant.

Real voltage sources, such as batteries, power supplies, piezoelectric disks, generators, steam turbines, wall outlets, etc. have an internal source impedance (in series with the ideal voltage source), which is very important to understand.

Ideal current sources

An ideal current source is a fundamental electronics component that creates a constant current through a section of circuit, regardless of whatever else is connected to it. Since it is ideal, some circuit configurations are not allowed, such as open circuits, which would create an infinite voltage.

A water analogy would be a pump with a flow meter. It measures the amount of water flowing by per unit time and changes the speed of the pump so that the current flow is constant.

Real current sources, such as batteries, power supplies, piezoelectric disks, generators, etc. have an internal source impedance (in parallel with the source), which is very important to understand.

Real sources generally behave more like voltage sources than current sources, because the internal impedance in series is very low. A current source can be created from a voltage source with a circuit such as a *current mirror*.

Dependent Sources

A dependent source is either a voltage or a current source which is dependent upon another value within the circuit, usually another voltage or current. Typically, these are used in circuit modeling and analysis.

There are four main types of such sources.

Voltage-controlled voltage source (VCVS)

This is a voltage source whose value is controlled by another voltage elsewhere in the circuit. Its output will typically be given as

, where A is a gain term and $V_c$is a control voltage.

An example of a VCVS may be an idealized amplifier, where A is the gain of the amplifier.

Current-controlled voltage source (CCVS)

This is a voltage source whose value is controlled by a current elsewhere in the circuit. Its output is typically given as

, where A is a gain term and I_c is a control current.

Voltage-controlled current source (VCCS)

This is a current source whose value is controlled by a voltage elsewhere in the circuit. Its output is typically given as

, where A is a gain term and V_c is a control voltage.

Current-controlled current source (CCCS)

This is a current source whose value is controlled by a current elsewhere in the circuit. Its output is typically given as

, where A is a gain term and I_c is a control current.

An example of a CCCS is an idealized bipolar junction transistor, which may be thought of as a small current controlling a larger one. Specifically the base current, I_b is the control and the collector current I_c is the output.

Switch

A switch is a mechanical device that connects or disconnects two parts of a circuit.

A switch is a short circuit when it is on.

And it is a open circuit when it is off.

When you turn a switch on it completes a circuit that allows current to flow. When you turn the switch off it creates an air gap (depending on the type of switch), and since air is an insulator no current flows.

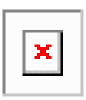
A switch is a device for making or breaking an electric circuit.

Usually the switch has two pieces of metal called contacts that touch to make a circuit, and separate to break the circuit. The contact material is chosen for its resistance to corrosion, because most metals form insulating oxides that would prevent the switch from working. Sometimes the contacts are plated with noble metals. They may be designed to wipe against each other to clean off any contamination. Nonmetallic conductors, such as conductive plastic, are sometimes used. The moving part that applies the operating force to the contacts is called the actuator, and may be a rocker, a toggle or dolly, a push-button or any type of mechanical linkage.

Contact Arrangements

Switches can be classified according to the arrangement of their contacts. Some contacts are normally open until closed by operation of the switch, while normally closed contacts are opened by the switch action. A switch with both types of contact is called a changeover switch.

The terms pole and throw are used to describe switch contacts. A pole is a set of contacts that belong to a single circuit. A throw is one of two or more positions that the switch can adopt. These terms give rise to the following abbreviations.



- S (single), D (double).
- T (throw), CO (changeover).
- CO = DT.

(single|double) pole ((single|double) throw|changeover)

- **SPST** = single pole single throw, a simple on-off switch.
- **SPDT** = single pole double throw, a simple changeover or on-off-on switch.
- **SPCO** = single pole changeover, equivalent to SPDT.
- **DPST** = double pole single throw, equivalent to two SPST switches controlled by a single mechanism.
- **DPDT** = double pole double throw, equivalent to two SPDT switches controlled by a single mechanism.
- **DPCO** = double pole changeover, equivalent to DPDT.

Switches with larger numbers of poles or throws can be described by replacing the "S" or "D" with a number.

Biased Switches

A biased switch is one containing a spring that returns the actuator to a certain position. The "on-off" notation can be modified by placing parentheses around all positions other than the resting position. For example, an (on)-off-(on) switch can be switched on by moving the actuator in either direction away from the centre, but returns to the central off position when the actuator is released.

The momentary push-button switch is a type of biased switch. This device makes contact when the button is pressed and breaks when the button is released.

Special Types

Switches can be designed to respond to any type of mechanical stimulus: for example, vibration (the trembler switch), tilt, air pressure, fluid level (the float switch), the turning of a key (key switch), linear or rotary movement (the limit switch or microswitch).

The mercury tilt switch consists of a blob of mercury inside a glass bulb. The two contacts pass through the glass, and are shorted together when the bulb is tilted to make the mercury roll on to them. The advantage of this type of switch is that the liquid metal flows around particles of dirt and debris that might otherwise prevent the contacts of a conventional switch from closing.

See also

- Other components
- Wikipedia: Category: Components
- Wikipedia: Category: Solid state switches
- Audio for robotics
- Wikipedia: Electronic components
- Wikipedia: Resistors and Capacitors
- Wikipedia: Batteries
- Wikipedia: * Batteries, Rechargeable
- Wikipedia: Capacitors
- Wikipedia: Cathode ray tubes
- Wikipedia: Circuit breakers
- Wikipedia: Connectors
- Wikipedia: Crystal filters
- Diodes
- Wikipedia: Diodes
- Wikipedia: Filters

- Wikipedia: Fuses
- Identification
- Wikipedia: Inductors
- Integrated circuits
- Wikipedia: Integrated circuits
- Wikipedia: Lasers
- Loudspeakers
- * Loudspeakers, Enclosures
- Wikipedia: Loudspeakers
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- Wikipedia: Piezoelectricity
- Power sources
- Wikipedia: Printed circuit boards
- Wikipedia: Rectifiers
- Wikipedia: * Rectifiers, Silicon-controlled (SCRs)
- Software development
- Wikipedia: * Rectifiers, Triacs
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- * Resistors, Light dependent
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- Wikipedia: Transistors
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- Wikipedia: Trisils
- Vacuum tubes
- Wikipedia: Vacuum tubes
- Wikipedia: Varistors

DC Voltage and Current Laws

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Ohm's Law

Ohm's law describes the relationship between voltage, current, and resistance.Voltage and current are proportional at a given temperature:

Voltage (V) is measured in volts (V); Current (I) in amperes (A); and resistance (R) in ohms (Ω).

In this example, the current going through any point in the circuit, I, will be equal to the voltage V divided by the resistance R.

In this example, the voltage across the resistor, V, will be equal to the supplied current, I, times the resistance R.

If two of the values (*V*, *I*, or *R*) are known, the other can be calculated using this formula.

Any more complicated circuit has an equivalent resistance that will allow us to calculate the current draw from the voltage source. Equivalent resistance is worked out using the fact that all resistor are either in parallel or series. Similarly, if the circuit only has a current source, the equivalent resistance can be used to calculate the voltage dropped across the current source.

Kirchoff's Voltage Law

Kirchoff's Voltage Law (KVL):

> The sum of voltage drops around any loop in the circuit that starts and ends at the same place must be zero.

Voltage as a Physical Quantity

1. Voltage is the potential difference between two charged objects.
2. Potentials can be added or subtracted in series to make larger or smaller potentials as is commonly done in batteries.
3. Electrons flow from areas of high potential to lower potential.
4. All the components of a circuit have resistance that acts as a potential drop.

Kirchoff's Current Law

Kirchoff's Current Law (KCL):

> The sum of all current entering a node must equal the sum of all currents leaving the node.

KCL Example

$-I_1 + I_2 + I_3 = 0 \leftrightarrow I_1 = I_2 + I_3$

$I_1 - I_2 - I_3 - I_4 = 0 \leftrightarrow I_2 + I_3 + I_4 = I_1$

Here is more about Kirchhoff's laws, which can be integrated here

Consequences of KVL and KCL

Voltage Dividers

If two circuit elements are in series, there is a voltage drop across each element, but the current through both must be the same. The voltage at any point in the chain divides according to the resistances. A simple circuit with two (or more) resistors in series with a source is called a voltage divider.

Figure A: Voltage Divider circuit.

Consider the circuit in Figure A. According to KVL the voltage

is dropped across resistors

and

. If a current i flows through the two series resistors then by Ohm's Law.

.

So

Therefore

Similary if

is the voltage across

then

In general for n series resistors the voltage dropped across one of them say

is

Where

Voltage Dividers as References

Clearly voltage dividers can be used as references. If you have a 9 volt battery and you want 4.5 volts, then connect two equal valued resistors in series and take the reference across the second and ground. There are clearly other concerns though, the first concern is current draw and the effect of the source impedance. Clearly connecting two 100 ohm resistors is a bad idea if the source impedance is, say, 50 ohms. Then the current draw would be 0.036 mA which is quite large if the battery is rated, say, 200 milliampere hours. The loading is more annoying with that source impedance too, the reference voltage with that source impedance is

. So clearly, increasing the order of the resistor to at least 1 k

is the way to go to reduce the current draw and the effect of loading. The other problem with these voltage divider references is that the reference cannot be loaded if we put a 100 Ω resistor in parallel with a 10 kΩ resistor. When the voltage divider is made of two 10 kΩ resistors, then the resistance of the reference resistor becomes somewhere near 100 Ω. This clearly means a terrible reference. If a 10 MΩ resistor is used for the reference resistor will still be some where around 10 kΩ but still probably less. The effect of tolerances is also a problem; if the resistors are rated 5% then the resistance of 10 kΩ resistors can vary by ±500 Ω. This means more inaccuracy with this sort of reference.

Current Dividers

If two elements are in parallel, the voltage across them must be the same, but the current divides according to the resistances. A simple circuit with two (or more) resistors in parallel with a source is called a current divider.

Figure B: Parallel Resistors.

If a voltage V appears across the resistors in Figure B with only

and

for the moment then the current flowing in the circuit, before the division, i is according to Ohms Law.

Using the equivalent resistance for a parallel combination of resistors is

(1)

The current through

according to Ohms Law is

(2)

Dividing equation (2) by (1)

Similarly

In general with n Resistors the current

is

Or possibly more simply

Where

Nodal Analysis

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Nodes

A node is a section of a circuit which connects components to each other. All of the current entering a node must leave a node, according to Kirchoff's Current Law. Every point on the node is at the same voltage, no matter how close it is to each component, because the connections between components are perfect conductors. This voltage is called the node voltage, and is the voltage difference between the node and an arbitrary reference, the ground point. The ground point is a node which is defined as having zero voltage. The ground node should be chosen carefully for convenience. Note that the ground node does not necessarily represent an actual connection to ground, it is just a device to make the analysis simpler. For example, if a node has a voltage of 5 Volts, then the voltage drop between that node and the ground node will be 5 Volts.

Note that in real circuits, nodes are made up of wires, which are not perfect conductors, and so the voltage is not perfectly the same everywhere on the node. This distinction is only important in demanding applications, such as low noise audio, high speed digital circuits (like modern computers), etc.

Nodal Analysis

Nodal analysis is a formalized procedure based on KCL equations.

Steps:

1. Identify all nodes.
2. Choose a reference node. Identify it with reference (ground) symbol. A good choice is the node with the most branches, or a node which can immediately give you another node voltage (e.g., below a voltage source).
3. Assign voltage variables to the other nodes (these are node voltages.)
4. Write a KCL equation for each node (sum the currents leaving the node and set equal to zero). Rearrange these equations into the form A*V1+B*V2=C (or similar for equations with more voltage variables.)
5. Solve the system of equations from step 4. There are a number of techniques that can be used: simple substitution, Cramer's rule, the adjoint matrix method, etc.

Complications in Nodal Analysis

1. Dependent Current Source

Solution: Write KVL equations for each node. Then express the extra variable (whatever the current source depends on) in terms of node voltages. Rearrange into the form from step 4 above. Solve as in step 5.

2. Independent Voltage Source
Problem: We know nothing about the current through the voltage source. We cannot write KCL equations for the nodes the voltage source is connected to.

Solution: If the voltage source is between the reference node and any other node, we have been given a 'free' node voltage: the node voltage must be equal to the voltage source value! Otherwise, use a 'super-node', consisting of the source and the nodes it is connected to. Write a KCL equation for all current entering and leaving the super-node. Now we have one equation and two unknowns (the node voltages). Another equation that relates these voltages is the equation provided by the voltage source (V2-V1=source value). This new system of equations can be solved as in Step 5 above.

3. Dependent Voltage Source
Solution: Same as an independent voltage source, with an extra step. First write a super-node KCL equation. Then write the source controlling quantity (dependence quantity?) in terms of the node voltages. Rearrange the equation to be in the A*V1+B*V2=C form. Solve the system as above.

Example

Given the Circuit below, find the voltages at all nodes.

node 0:

(defined as ground node)
node 1:

(free node voltage)
node 2:

node 3:

which results in the following system of linear equations:

therefore, the solution is:

Another solution with KCL would be to solve node in terms of node 2;

External Links

- Free Nodal Analysis EBook by Dr. Yaz Li

Mesh Analysis

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Meshes

A 'mesh' (also called a loop) is simply a path through a circuit that starts and ends at the same place. For the purpose of mesh analysis, a mesh is a loop that does not enclose other loops.

Mesh Analysis

Similar to nodal analysis, mesh analysis is a formalized procedure based on KVL equations. A caveat: mesh analysis can only be used on 'planar' circuits (i.e. there are no crossed, but unconnected, wires in the circuit diagram.)

Steps:

1. Draw circuit in planar form (if possible.)
2. Identify meshes and name mesh currents. Mesh currents should be in the clockwise direction. The current in a branch shared by two meshes is the difference of the two mesh currents.
3. Write a KVL equation in terms of mesh currents for each mesh.
4. Solve the resulting system of equations.

Complication in Mesh Analysis

1. Dependent Voltage Sources

Solution: Same procedure, but write the dependency variable in terms of mesh currents.

2. Independent Current Sources

Solution: If current source is not on a shared branch, then we have been given one of the mesh currents! If it is on a shared branch, then use a 'supermesh' that encircles the problem branch. To make up for the mesh equation you lose by doing this, use the mesh current relationship implied by the current source (i.e.

).

3. Dependent Current Sources

Solution: Same procedure as for an independent current source, but with an extra step to eliminate the dependency variable. Write the dependency variable in terms of mesh currents.

Example

Given the Circuit below, find the currents

,

.

The circuit has 2 loops indicated on the diagram. Using KVL we get:

Loop1:

Loop2:

Simplifying we get the simultaneous equations:

solving to get:

Thevenin and Norton Equivalent Circuits

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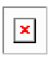
Source Transformation

Any linear time invariant network of impedances can be reduced to one equivalent impedance. In particular, any network of sources and resistors can be reduced to one ideal source and one resistor, in either the Thevenin or Norton configurations. In this way, a complicated network attached to a load resistor can be reduced to a single voltage divider (Thevenin) or current divider (Norton).



Thevenin and Norton equivalents let you replace a Voltage source in series with a resistor by a current source in parallel with a resistor, or vice versa. This is called a source transformation.

The point to be noted is that the block that is replaced with such an equivalent should be linear and time invariant, i.e. a linear change in the electrical source in that block produces a linear change in the equivalent source, and the behavior can be replicated if the initial conditions are replicated. **The above shown transformation figures are true only if the circuit contains at least one independent voltage or current source. If the circuit comprises only dependent sources then Thevenin equivalent consists of R_{Th} alone** See This to get a clear idea

Thevenin Equivalents

The Thevenin equivalent circuit of a (two-terminal) network consists of a voltage source in series with a resistor. The Thevenin equivalent will have the same output voltage and current regardless of what is attached to the terminals.

Techniques For Finding Thevenin Equivalents

- Network contains no sources (only resistors): The Thevenin resistance is equal to the equivalent resistance of the network. The Thevenin voltage is zero.

- Basic: Works for any network except one with no independent sources. Find the voltage across the terminals (with positive reference at terminal A) when they are open-circuited. Find the current from terminal A to terminal B when they are short-circuited. Then

The Thevenin voltage source value is equivalent to the open-circuit voltage.

If the network has no dependent sources, the independent sources can be zeroed, and the Thevenin resistance is equal to the equivalent resistance of the network with zeroed sources. Then, find

.

- Only Dependent Sources:

If the network has only dependent sources, either attach a test voltage source to the terminal points and measure the current that passes from the positive terminal, or attach a test current source to the terminal points and measure the voltage difference across the terminals. In both cases you will have values for

and

, allowing you to use the

relation to find the Thevenin resistance.

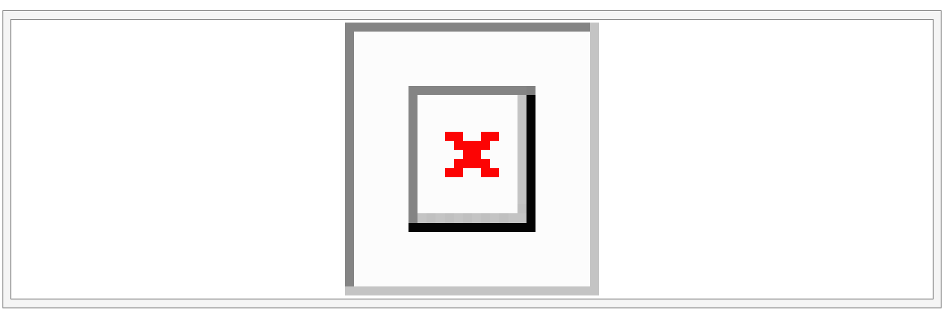
Norton Equivalents

Norton equivalents can be found by performing a source transformation on the Thevenin equivalent. The Norton Equivalent of a Thevenin Equivalent consists of a current source,

in parallel with

.

Thevenin and Norton Equivalent



The steps for creating the Equivalent are:

1. Remove the load circuit.
2. Calculate the voltage, V, at the output from the original sources.
3. Now replace voltage sources with shorts and current sources with open circuits.
4. Replace the load circuit with an imaginary ohm meter and measure the total resistance, R, looking back into the circuit, with the sources removed.
5. The equivalent circuit is a voltage source with voltage V in series with a resistance R in series with the load.

The Thevenin Equivalent is determined with

as the load as shown in Figure 1. The first step is to open circuit

. Then the voltage v is calculated with

open circuited must be calculated. The voltage across

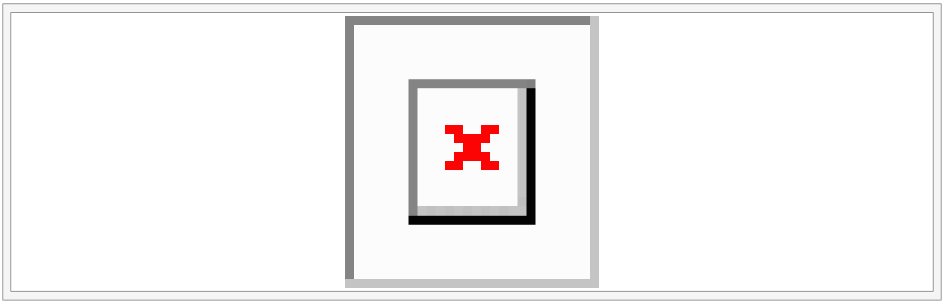
is

this is because no current flows in the circuit so the voltage across

must be

by KVL.

Since this circuit does not contain any dependent sources, all that needs to be done is for all the Independent Voltage sources to be shorted and for all Independent Current Sources to be open circuited. This results in the circuit shown in Figure 2.



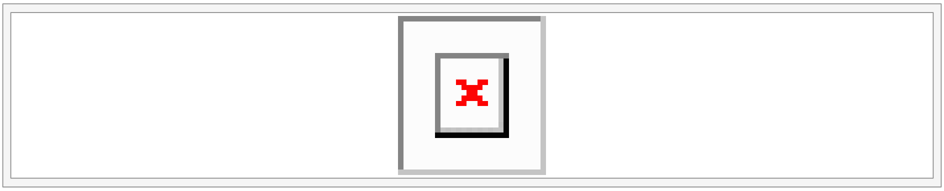
Now the Thevenin Resistance is calculated looking into the two nodes. The Thevenin resistance is clearly

. The Thevenin Equivalent is shown in Figure 3 and

and

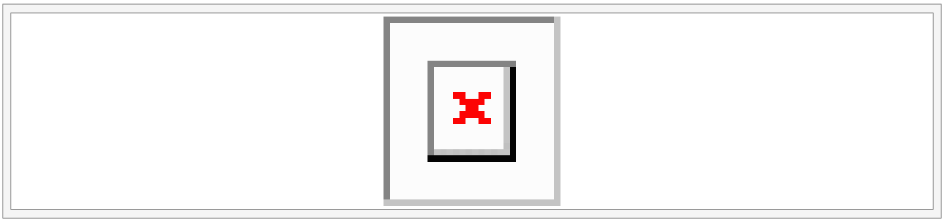
have the values shown below.

(1)



The Norton Equivalent is created by doing a source transformation using

.(2)



If

and

and

then

As a final note if the voltage across

is calculate by Voltage Divider Rule using the Thevenin Equivalent circuit in Figure 3.

(3)

If the value of

form equation 1 is substituted into equation 3.

(4)

Now look at Figure 1 and calcute

by voltage divider rule it has the same value as equation 4. If the current through

is calculated in Figure 4 by current divider rule.

Substituting equation 2 into 5.

If equation 4 and Ohm's Law are used to get the voltage across

equation 3 is reached.

Please note: The "||", a symbol that is used as an operator here, holds higher precedence than the "+" operator. As such, it is evaluated before a sum.

See Norton's theorem and Thevenin's theorem for more examples. - Omegatron 18:22, 4 Jun 2005 (UTC)

Superposition

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Superposition Principle

(a)

(b)

(c)

Figure 1: The circuits showing the linearity of resistors.

Most basic electronic circuits are composed of linear elements. Linear elements are circuit elements which follow Ohm’s Law. In Figure 1 (a) with independent voltage source, V_1, and resistor, R, a current i_1 flows. The current i_1 has a value according to Ohm's Law. Similarly in Figure 1 (b) with independent voltage source, V2, and resistor, R, a current i_2 flows. In Figure 1 (c) with independent voltage sources, V1 and V2, and resistor, R, a current i flows. Using Ohm's Law equation 1 is reached. If some simple algebra is used then equation 2 is reached. But V_1/R has a value i_1 and the other term is i_2 this gives equation 3. This is basically what the Superposition Theorem states.

(1)

(2)

(3)

The **Superposition Theorem** states that the effect of all the sources with corresponding stimuli on a circuit of linear elements is equal to the algebraic sum of each individual effect. Each individual effect is calculated by removing all other stimuli by replacing voltage sources with short circuits and current sources with open circuits. Dependent sources can be removed as long as the controlling stimuli is not set to zero. The process of calculating each effect with one stimulus connected at a time is continued until all the effects are calculated. If kth stimulus is denoted sk and the effect created by sk denoted ek.

(4)

The steps for using superposition are as follows:

1. Calculate the effect of each source in turn with all other independent voltage sources short circuited and independent current sources open circuited.
2. Sum these effects to get the complete effect.

Note: the removal of each source is often stated differently as: replace each voltage source with its internal resistance and each current with its internal resistance. This is identical to what has been stated above. This is because a real voltage source consists of an independent voltage source in series with its internal resistance and a real current source consists of an independent current source in parallel with its internal resistance.

Superposition Example

Figure 2: The circuit for the example.

Problem: Calculate the voltage, v, across resistor R_1.

Step 1: Short circuit V_2 and solve for v_1. By voltage divider rule.

(5)

Short circuit V_1 and solve for v_2. By voltage divider rule.

(6)

Step 2: Sum the effects.

Using equations 5 and 6.

If

and

then

Diagnostic Equipment

Diagnostic and Testing Equipment

There is a wide array of devices used to test and diagnose electronic equipment. This chapter will attempt to explain the differences and different types of equipment used by electronics technicians and engineers.

Ammeter

An ammeter measures current.Current in electronics is usually measured in mA which are called milliamperes, which are 1/1000s of an ampere.
. The ammeter's terminals must be *in series* with the current being measured. Ammeters have a small resistance (typically 50 ohms) so that they only have a small effect on the current.

Basically an ammeter consists of a coil that can rotate inside a magnet, but a spring is trying to push the coil back to zero. The larger the current that flows through the coil, the larger the angle of rotation, the torque (= a rotary force) created by the current being counteracted by the return torque of the spring.

. Usually ammeters are connected in parallel with various switched resistors that can extend the range of currents that can be measured. Assume, for example, that the basic ammeter is "1000 ohms per volt", which means that to get the full-scale deflection of the pointer a current of 1 mA is needed (1 volt divided by 1000 ohms is 1 mA - see "Ohm's Law").
. To use that ammeter to read 10 mA full-scale it is *shunted* with another resistance, so that when 10 mA flows, 9 mA will flow through the shunt, and only 1 mA will flow through the meter. Similarly, to extend the range of the ammeter to 100 mA the shunt will carry 99 mA, and the meter only 1 mA.

Ohmmeter

An ohmmeter measures resistance.The two terminals of ohmmeter are each placed on a terminal of the resistance being measured. This resistance should be isolated from other effects. (It should be taken out of a circuit, if it is in one.)

Ohmmeters are basically ammeters that are *connected to an internal battery, with a suitable resistance in series*. Assume that the basic ammeter is "1000 ohms per volt", meaning that 1 mA is needed for full-scale deflection. When the external resistance that is connected to its terminals is zero (the leads are connected together at first for calibration), then the internal, variable, resistor in series with the ammeter is adjusted so that 1 mA will flow; that will depend on the voltage of the battery, and as the battery runs down that setting will change. The full scale point is marked as zero resistance. If an external resistance is then connected to the terminals that causes only half of the current to flow (0.5 mA in this example), then the external resistance will equal the internal resistance, and the scale is marked accordingly. When no current flows, the scale will read infinity resistance. The scale of an ohmmeter is NOT linear.Ohmmeters are usually usuful in cheking the short circuit and open circuit in boards.its about sss

Voltmeter

A voltmeter measures voltage.The voltmeter's terminals must be *in parallel* with the voltage being measured. Voltmeters have a large resistance (typically 1 megaohm), so that they only have a small effect on the voltage.

Multimeter

A multimeter is a combination device, (usually) capable of measuring current, resistance, or voltage. Most modern models measure all three, and include other features such as a diode tester, which can be used to measure continuity in circuits (emitting a loud 'beep' if there is a short).

Oscilloscope

An oscilloscope, commonly called a 'scope' by technicians, is used to display a voltage waveform on a screen, usually graphing voltage as a function of time.

Spectrum Analyzer

Spectrum analyzer shows voltage (or power) densities as function of frequency on radio frequency spectrum. Spectrum analyzer can use analog frequency scanning principle (like radio receiver always changing frequency and measuring receiving amplitude) or digital sampling and FFT (Fast Fourier Transformation).

Logic analyzer

A logic analyzer is, in effect, a specialised oscilloscope. The key difference between an analyzer and an oscilloscope is that the analyzer can only display a digital (on/off) waveform, whereas an oscilloscope can display any voltage (depending on the type of probe connected). The other difference is that logic analyzers tend to have many more signal inputs than oscilloscopes - usually 32 or 64, versus the two channels most oscilloscopes provide. Logic analyzers can be very useful for debugging complex logic circuits, where one signal's state may be affected by many other signals.

File:Logic probe new.jpg

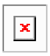
Frequency counter

A frequency counter is a relatively simple instrument used to measure the frequency of a signal in Hertz (cycles per second). Most counters work by counting the number of signal cycles that occur in a given time period (usually one second). This count is the frequency of the signal in Hertz, which is displayed on the counter's display.

Electrometer

A voltmeter with extremely high input resistance capable of measuring electrical charge with minimal influence to that charge. Ubiquitous in nucleonics, physics and bio-medical disciplines. Enables the direct verification of charge measured in coulombs according to Q=CV. Additionally, electrometers can generally measure current flows in the femtoampere range, i.e. .000000000000001 ampere.

Signal Generator



DC Circuit Analysis

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DC Circuit Analysis

In this chapter, capacitors and inductors will be introduced (without considering the effects of AC current.) The big thing to understand about Capacitors and Inductors in DC Circuits is that they have a transient (temporary) response. During the transient period, capacitors build up charge and stop the flow of current (eventually acting like infinite resistors.) Inductors build up energy in the form of magnetic fields, and become more conductive. In other words, in the steady-state (long term behavior), capacitors become open circuits and inductors become short circuits. Thus, for DC analysis, you can replace a capacitor with an empty space and an inductor with a wire. The only circuit components that remain are voltage sources, current sources, and resistors.

Capacitors and Inductors at DC

DC steady-state (meaning the circuit has been in the same state for a long time), we've seen that capacitors act like open circuits and inductors act like shorts. The above figures show the process of replacing these circuit devices with their DC equivalents. In this case, all that remains is a voltage source and a lone resistor. (An AC analysis of this circuit can be found in the AC section.)

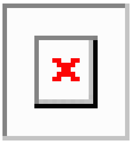
Resistors

If a circuits contains only resistors possibly in a combination of parallel and series connections then an equivalent resistance is determined. Then Ohm's Law is used to determine the current flowing in the main circuit. A combination of voltage and current divider rules are then used to solve for other required currents and voltages.

Simplify the following:

(a)

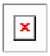
(b)



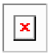
(c)

Figure 1: Simple circuits series circuits.

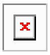
The circuit in Figure 1 (a) is very simple if we are given R and V, the voltage of the source, then we use Ohm's Law to solve for the current. In Figure 1 (b) if we are given R1, R2 and V then we combine the resistor into an equivalent resistors noting that are in series. Then we solve for the current as before using Ohm's Law. In Figure 1 (c) if the resistors are labeled clockwise from the top resistor R1, R2 and R3 and the voltage source has the value: V. The analysis proceeds as follows.



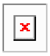
This is the formula for calculating the equivalent resistance of series resistor. The current is now calculated using Ohm's Law.

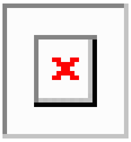


If the voltage is required across the third resistor then we can use voltage divider rule.

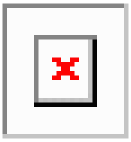


Or alternatively one could use Ohm's Law together with the current just calculated.





(a)



(b)

Figure 2: Simple parallel circuits.

In Figure 2 (a) if the Resistor nearest the voltage source is R1 and the other resistor R2. If we need to solve for the current i. Then we precede as before first we calculate the equivalent resistance then use Ohm's Law to solve for the current. The resistance of a parallel combination is:

So the current, *i*, flowing in the circuit is, by Ohm's Law:

If we need to solve for current through R2 then we can use current divider rule.

(1)

But it would probably have been simpler to have used the fact that V most be dropped across R2. This means that we can simply use Ohm's Law to calculate the current through R2. The equation is just equation 1. In Figure 2 (b) we do exactly the same thing except this time there are three resistors this means that the equivalent resistance will be:

Using this fact we do exactly the same thing.

(a)

(b)

(c)

Figure 3: Combined parallel and series circuits

In Figure 3 (a), if the three resistors in the outer loop of the circuit are R1, R2 and R3 and the other resistor is R4. It is simpler to see what is going on if we combine R2 and R3 into their series equivalent resistance

. It is clear now that the equivalent resistance is R1 in series with the parallel combination of

and R4. If we want to calculate the voltage across the parallel combination of R4 and

then we just use voltage divider.

If we want to calculate the current through R2 and R3 then we can use the voltage across

and Ohm's law.

Or we could calculate the current in the main circuit and then use current divider rule to get the current.

In Figure 3 (b) we take the same approach simplifying parallel combinations and series combinations of resistors until we get the equivalent resistance.

In Figure 3 (c) this process doesn't work then because there are resistors connected in a delta this means that there is no way to simplify this beyond transforming them to a star or wye connection.

Note: To calculate the current draw from the source the equivalent resistance always must be calculated. But if we just need the voltage across a series resistor this may be necessary. If we want to calculate the current in parallel combination then we must use either current divider rule or calculate the voltage across the resistor and then use Ohm's law to get the current. The second method will often require less work since the current flowing from the source is required for the use of current divider rule. The use of current divider rule is much simpler in the case when the source is a current source because the value of the current is set by the current source.

Star Network

The above image shows three points 1, 2, and 3 connected with resistors R_1, R_2, and R_3 with a common point. Such a configuration is called a *star network* or a *Y-connection*.

The above image shows three points 1, 2, and 3 connected with resistor R_{12}, R_{23}, and R_{31}. The configuration is called a *delta network* or *delta connection*.

We have seen that the series and parallel networks can be reduced by the use of simple equations. Now we will derive similar relations to convert a star network to delta and vice versa. Consider the points 1 and 2. The resistance between them in the star case is simply

$$R_1 + R_2$$

For the delta case, we have

$$R_{12} \,||\, (R_{31} + R_{23})$$

We have similar relations for the points 2, 3 and 3, 1. Making the substitution $r_1 = R_{23}$ etc., we have, simplifying,

in the most general case. If all the resistances are equal, then $R = r/3$.

Measuring Instruments

Measuring Instruments

Ammeters

Ammeters are devices that measure current. Current in electronics is usually measured in mA which are called milliamperes, which are 1/1000s of an ampere.

..... Basically an ammeter consists of a coil that can rotate inside a magnet, but a spring is trying to push the coil back to zero. The larger the current that flows through the coil, the larger the angle of rotation, the torque (= a rotary force) created by the current being counteracted by the return torque of the spring.

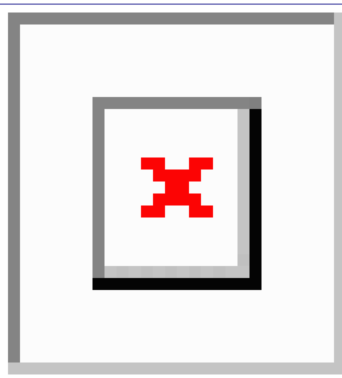
..... Usually ammeters are connected in parallel with various switched resistors that can extend the range of currents that can be measured. Assume, for example, that the basic ammeter is "1000 ohms per volt", which means that to get the full-scale deflection of the pointer a current of 1 mA is needed (1 volt divided by 1000 ohms is 1 mA - see "Ohm's Law").

..... To use that ammeter to read 10 mA full-scale it is *shunted* with another resistance, so that when 10 mA flows, 9 mA will flow through the shunt, and only 1 mA will flow through the meter. Similarly, to extend the range of the ammeter to 100 mA the shunt will carry 99 mA, and the meter only 1 mA.

Ohmmeters

Ohmmeters are basically ammeters that are *connected to an internal battery, with a suitable resistance in series*. Assume that the basic ammeter is "1000 ohms per volt", meaning that 1 mA is needed for full-scale deflection. When the external resistance that is connected to its terminals is zero (the leads are connected together at first for calibration), then the internal, variable, resistor in series with the ammeter is adjusted so that 1 mA will flow; that will depend on the voltage of the battery, and as the battery runs down that setting will change. The full scale point is marked as zero resistance. If an external resistance is then connected to the terminals that causes only half of the current to flow (0.5 mA in this example), then the external resistance will equal the internal resistance, and the scale is marked accordingly. When no current flows, the scale will read infinity resistance. The scale of an ohmmeter is NOT linear.Ohmmeters are usually useful in checking the short circuit and open circuit in boards.

Multimeters



A digital multimeter

Multimeters contain Ohmeters, Voltmeters, Ammeters and a variety of capabilities to measure other quantities. AC and DC voltages are most often measurable. Frequency of AC voltages. Multimeters also feature a continuity detector, basically an Ohmmeter with a beeper if the multimeter sees less than 100 Ω then it beeps otherwise it is silent. This is very useful for finding whether components are connected when debugging or testing circuits. Multimeters are also often able to measure capacitance and inductance. This may be achieved using a Wien bridge. A diode tester is also generally onboard, this allows one to determine the anode and cathode of an unknown diode. A LCD display is also provided for easily reading of results.

Wikipedia:Multimeter

Electronics Laboratory Instruments

Oscilloscope

The instrument is used to view AC waveforms. For better explanation of the oscilloscope.

Spectrum Analyzer

Wikipedia:Spectrum_Analyzer

Signal Generator

This instrument is used to generate low voltage AC signals. Most common signal generators can create sinusoidal(sine), triangular and square waves of various frequencies. They are used in conjunction with the oscilloscope to test analogue circuits.

Wikipedia:Signal_Generator

Logic Probe

This instrument generates high and low logic states to test digital circuits. If a logic probe is not available a square wave through a signal generator can be used. Square waves can also be used to test the response time of a digital circuits.

Wikipedia:Logic Probe

Noise in electronic circuits

Electrical Noise
: any unwanted form of energy tending to interfere with the proper and easy reception and reproduction of wanted signals.

Classification

Based on Origin

1. External noise
    1. Atmospheric
    2. Extraterrestrial
        1. solar
        2. Cosmic
    3. Industrial

2. Internal noise
    1. Thermal Agitation Noise
    2. Shot Noise
    3. Transit Time Noise
    4. Flicker Noise
    5. Miscellaneous Sources

Thermal noise

Thermal Agitation Noise

Also known as **Johnson noise or White noise**.

where k = Boltzmann's constant = 1.38×10^{-23} J/K

T = absolute temperature, K = 273 + °C

δf = bandwidth of interest

P_n = maximum noise power output of a resistor

Shot Noise

Wikipedia has related information at ***shot noise#In electronic devices***

where i_n = r.m.s. shot-noise current

e = charge of an electron = 1.6×10^{-19}C

i_p = direct diode current

δf = bandwidth of system

Noise Calculations

Addition due to several sources

noise voltages:

,

...and so on, then

where $R_{tot} = R_1 + R_2 + ...$

Addition due to Cascaded Amplifier stages

$R_{eq} = R_1 + R'_2$

Analog Noise Models

CMOS

BJT

Noise in digital circuits:

Methods of reducing noise

Differential signaling

Differential signaling is a method of transmitting information electrically by means of two complementary signals sent on two separate wires. The technique can be used for both analogue signaling, as in some audio systems, and digital signaling, as in RS-422, RS-485, PCI Express and USB.

Good grounding

An ideal signal ground maintains zero voltage regardless of how much electrical current flows into ground or out of ground.

References

Kennedy, George *'Electronic Communication Systems'* , 3rd Ed. ISBN 0-07-034054-4

Chapter 2: AC Circuits

AC Circuits

Electronics | Foreword | Basic Electronics | Complex Electronics | Electricity | Machines | History of Electronics | Appendix | edit

Relationship between Voltage and Current

Resistor

In a resistor, the current is in phase with the voltage always. This means that the peaks and valleys of the two waveforms occur at the same times. Resistors can simply be defined as devices that perform the sole function of inhibiting the flow of current through an electrical circuit. Resistors are commercially available having various standard values, nevertheless variable resistors are also made called potentiometers, or pots for short.

Capacitor

The capacitor is different from the resistor in several ways. First, it consumes no real power. It does however, supply reactive power to the circuit. In a capacitor, as voltage is increasing the capacitor is charging. Thus a large initial current. As the voltage peaks the capacitor is saturated and the current falls to zero. Following the peak the circuit reverses and the charge leaves the capacitor. The next half of the cycle the circuit runs mirroring the first half.

The relationship between voltage and current in a capacitor is:

. This is valid not only in AC but for any function v(t). As a direct consequence we can state that in the real world, the voltage across a capacitor is always a continuous function of the time.

If we apply the above formula to a AC voltage (i.e.

), we get for the current a 90° phase shift:

.

In an AC circuit, current leads voltage by a quarter phase or 90 degrees. Note that while in DC circuits after the initial charge or discharge no current can flow, in AC circuits a current flows all the time into and out of the capacitor, depending on the impedance in the circuit. This is similar to the resistance in DC circuits, except that the impedance has 2 parts; the resistance included in the circuit, and also the reactance of the capacitor, which depends not only on the size of the capacitor, but also on the frequency of the applied voltage. In a circuit that has DC applied plus a signal, a capacitor can be used to block the DC, while letting the signal continue.

Inductor

In inductors, current is the negative derivative of voltage, meaning that however the voltage changes the current tries to oppose that change. When the voltage is not changing there is no current and no magnetic field.

In an AC Circuit, voltage leads current by a quarter phase or 90 degrees.

Voltage Defined as the derivative of the flux linkage:

Resonance

A circuit containing resistors, capacitors, and inductors is said to be in resonance when the reactance of the inductor cancels that of the capacitor to leave the resulting total resistance of the circuit to be equal to the value of the component resistor. The resonance state is achieved by fine tuning the frequency of the circuit to a value where the resulting impedance of the capacitor cancels that of the inductor, resulting in a circuit that appears entirely resistive.

See also

AC Voltage:

When the Voltage between two points is changing continuously with time then the voltage is called AC Voltage. For AC Voltages there will be no constant value so we define it by the average value called RMS value RMS means Root Means Square.

Phasors

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Phasors

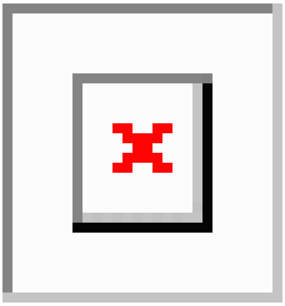


Figure Two: Polar Notation

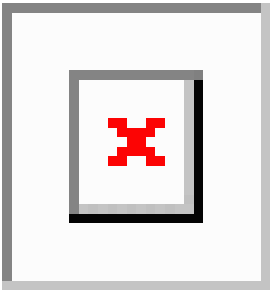
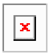


Figure One: Rectangular Notation

Phasors provide a simple means of analyzing linear circuits. At the heart of phasor analysis lies Euler's formula:



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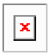
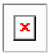
A complex exponential can also be expressed as





is called a phasor. It contains information about the magnitude and phase of a sinusoidal signal, but not the frequency or time. This simplifies use in circuit analysis, since most of the time, all quantities in the circuit will have the same frequency. (For circuits with sources at different frequencies, the principle of superposition must be used.)

A shorthand phasor notation is:

Note that this is simply a polar form, and can be converted to rectangular notation by (see figure one):

and back again by (see figure two):

Sinusoidal Signals

To begin, we must first understand what sinusoidal signals are. Sinusoidal signals can be represented as

where A is the amplitude,

is the frequency in radians per second, and

is the phase angle in degrees(phase shift). We can return to the sinusoidal signal by taking the real part of Euler's formula:

For the moment, consider single-frequency circuits. Every steady state current and voltage will have the same basic form:

where

is a phasor. So we can "divide through" by to get phasor circuit equations. We can solve these equations for some phasor circuit quantity

, multiply by

, and convert back to the sinusoidal form to find the time-domain sinusoidal steady-state solution.

Example

We have three sinusoidal signals with the same frequency added together:

In phasor notation, this is:

We can combine these terms to get one phasor notation. This is done first by separating the real and imaginary components:

The phasor notation can be written as:

Back to the time domain, we get the answer:

Footnotes

1. ↑
    - **j** is the Imaginary unit (
).
    - In electrical engineering, the imaginary unit is symbolized by j rather than the symbol *i* because *i* is used to denote current in electrical engineering.
    - The frequency of the wave, in Hz, is given by
      .

Impedance

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Definition

Impedance,
, is the quantity that relates voltage and current in the frequency domain. (The tilde indicates a phasor. An overscore or arrow may also be used.)

.

In rectangular form,

where *R* is the resistance and *X* is the reactance. Impedance is generally a function of frequency, i.e.

NOTE: $\omega = 2 \pi f$

where f is the frequency in cycles per second (f=50 or 60 Hertz usually, depending on the country concerned. Aircraft systems often use 400 Hertz.)

Reactance

Reactance (symbol) is the resistance to current flow of a circuit element that can store energy (i.e. a capacitor or an inductor), and is measured in ohms.

The reactance of an inductor of inductance (in Henries), through which an alternating current of angular frequency flows is given by:

The reactance of a capacitor of capacitance (in Farads) is given similarly:

The two formulae for inductive reactance and capacitive reactance create interesting counterpoints. Notice that for inductive reactance, as the frequency of the AC increases, so does the reactance. Hence, higher frequencies result in lower current. The opposite is true of capacitive reactance: The higher the frequency of AC, the less reactance a capacitor will present.

Similarly, a more inductive inductor will present more reactance, while a capacitor with more capacitance will yield less reactance.

Resistors

Resistors have zero reactance, since they do not store energy, so their impedance is simply

.

Capacitors

Capacitors have zero resistance, but do have reactance. it is store in the power . Their impedance is

where *C* is the capacitance in farads. The reactance of one microfarad at 50 Hz is -3183 ohms, and at 60 Hz it is -2653 ohms.

.

Inductors

Like capacitors, inductors have zero resistance, but have reactance. Their impedance is where *L* is the inductance in henries. The reactance of one henry at 50 Hz is 314 ohms, and at 60 Hz it is 377 ohms.

Circuit Analysis Using Impedance

Analysis in the frequency domain proceeds exactly like DC analysis, but all currents and voltages are now phasors (and so have an angle). Impedance is treated exactly like a resistance, but is also a phasor (has an imaginary component/angle depending on the representation.)

(In the case that a circuit contains sources with different frequencies, the principle of superposition must be applied.)

Note that this analysis only applies to the steady state response of circuits. For circuits with transient characteristics, circuits must be analyzed in the Laplace domain, also known as s-domain analysis.

Steady State

Steady State

That can be said to be the condition of "rest", after all the changes/alterations were made. This may imply, for examples, that nothing at all happens, or that a "steady" current flows, or that a circuit has "settled down" to final values - that is until the next disturbance occurs.

If the input signal is not time invariant, say if is a sinosoid, the steady state wont be invariant either. The response of a system can be considered to be composed of a transient response: the response to a disturbance, and the steady state response, in the absence of disturbance.

The transient part of the response tends to zero as time since a disturbance tends to infinity, so the steady state can be considered to be the response remaining as T -> infinity.

Chapter 3: Transient Analysis

RC Circuits

Electronics/RC Circuits

RL Circuits

Electronics/RL Circuits

LC Circuits

Electronics/LC Circuits

RCL Circuits

Electronics/RCL Circuits

Chapter 4: Analog Circuits

Analog Circuits

As explained later, digital signals can only take one of two values at any one point. Analog signals, however, can take any value within a range. In modern electronics, many traditionally analog circuits are being replaced with digital ICs for various reasons:

- Reduced cost:
  - Digital ICs can be programmed, meaning many different analog circuits can each be replaced with the same IC, reducing cost. For example, the same DSP chip might replace many different analog filters.
  - Digital ICs can be easily expanded to put multiple functions on the same chip. For example, a DSP chip replacing multiple analog filters at the same time.
  - Digital ICs can be reprogrammed without modifying the circuit, simplifying prototyping and field upgrades.
- Increased versatility:
  - A digital IC can have its settings changed arbitrarily while it is being operated, these settings can even be changed by software. The equivalent in an analog circuit might require expensive and complicated switching techniques.
- Numeric precision: once a signal is converted to digital data, distortion and circuit noise are no longer a significant issue. A cheap modern watch driven by a digital circuit (such as a quartz oscillator and a counter) is more precise than any analog or mechanical clock.
- Ease of storage: digital data, once recorded, does not degrade as easily as analog data.

Digital circuits are also becoming more prevalent where there are no analog analogues, such as computers. Although analogue computers exist, their utility is severely limited by comparison.

Analog circuits are still more suitable for many functions. One important category is interfaces. Digital circuits are usually inferior to analog circuits for receiving and transmitting signals.

- A common digital interface, the differential line, needs an analog circuit to function well. The receiver must filter out common mode interference by computing the analog difference between the two lines. Most digital interfaces are designed as analog, only a few legacy interfaces (which have poor performance) use entirely digital circuits.
- Many radio signals are simply too high frequency to work with existing digital circuits. Radio modulators, demodulators, mixers, transmitters, and receivers are still analog. Some signals are even too high frequency for transistor circuits of any kind to amplify efficiently, such as microwave signals, which are still transmitted using vacuum tubes.
- Signals must be conditioned before conversion to digital to avoid aliasing: analog filters remove unwanted parts of signals.
- Many devices, such as monitors, require analog control. Even LCD monitors require analog circuits, although they need not be as sophisticated as CRT analog circuits.
- Audio equipment requires analog circuits. Speakers must be driven by analog signals, microphones produce analog signals. Signal of a microphone must be conditioned before conversion to digital, this usually entails sophisticated analog circuits such as preamplifers, compressors, and filters.

Vacuum Tubes

Passive Versus Active Components

Passive components have no gain and are not valves

- **Voltage Regulator:** an **active component** which accepts a range of voltages and outputs one constant voltage.

Vacuum Tube equals Thermonic Valve

A Vacuum Tube is a container (usually of glass) from which the air is removed. Inside the tube are two or more "Elements".

- Cathode: (electron emitter) has an electrically heated filament (which you can usually see glow red) which spits out electrons that travel through the vacuum to the Anode (electron acceptor).

- Anode: Is a conductive (usually metal) plate that is connected to a positive voltage. The negative electrons flow from the Cathode to the Anode.

A vacuum tube with just Cathode and Anode elements is a DIODE. Current will flow only when the Anode has a positive voltage relative to the Cathode.

- Grid(s): metal gratings or grids are placed between the Cathode and Anode to produce devices that can amplify signals.

NOTE: A tube with 3 elements (one grid) is a TRIODE, with 2 grids a TETRODE, with 3 grids a PENTODE.

A Grid between the cathode and anode controls the flow of electrons. By applying a negative voltage to the grid it is possible to control the flow of electrons. This is the basis of the Vacuum Tube amplifier.

A problem with Vacuum Tubes is they are big, bulky, and often meant for applications involving a lot of power. They are very power hungry and are prone to breaking, which usually meant their casing broke and the Vacuum stopped being a Vacuum. However it is possible to scale up vacuum tubes to very high powers, and many high-powered transmitters for broadcast FM and TV use vacuum power tubes.

Vacuum tube based amplifiers have largely been replaced by semiconductor transistor based amplifiers, as they are low power and much more compact.

The voltage difference in the direction from the cathode to the anode is known as the forward bias and is the normal operating mode. If the voltage applied to the Anode becomes negative relative to the Cathode, no electrons will flow. This effect is used in vacuum tube Rectifiers.

In recent years, however, vacuum tubes have been making a comeback among audiophiles who believe that they offer a "fatter" and "warmer" sound. This is due to the fact that overdriven tubes bend the waveform off in a smooth curve, rather than the sharp cutoff associated with bipolar transistor amplifiers.

Klystron

A klystron is a vacuum tube used for production of microwave energy. This device is related to but not the same as a magnetron. The klystron was invented after the magnetron.

Klystrons work using a principle known as velocity modulation.

The klystron is a long narrow vacuum tube. There is an electron gun (heater, cathode, beam former) at one end and an anode at the other. In between is a series of donut shaped resonant cavity structures positioned so that the electron beam passes through the hole.

The first and last of the resonant cavities are electrically wired together.

At the cathode the electron beam is relatively smooth. There are natural slight increases and decreases in the electron density of the beam. As the beam passes through the holes of the resonant cavities, any changes in the electron beam cause some changes in the resting electro magnetic (EM) field of the cavities. The EM fields of the cavities begin to oscillate. The oscillating EM field of the cavities then has an effect on the electrons passing through, either slowing down or speeding up their passage.

As electrons are affected by the EM field of the first cavity they change their speed. This change in speed is called velocity modulation. By the time the electrons arrive at the last cavity there are definite groups in the beam. The groups interact strongly with the last cavity causing it to oscillate in a more pronounced way. Some of the last cavity's energy is tapped off and fed back to the first cavity to increase its oscillations. The stronger first cavity oscillations produce even stronger grouping of the electrons in the beam causing stronger oscillations in that last cavity and so on. This is positive feedback.

The output microwave energy is tapped of for use in high power microwave devices such as long range primary RADAR systems.

The klystron is a coherent microwave source in that it is possible to produce an output with a constant phase. This is a useful attribute when combined with signal processing to measure RADAR target attributes like Doppler shift.

Related microwave vacuum tubes are the Travelling Wave Tube (TWT) and the Travelling Wave Amplifier (TWA). A Hybrid device, which combines some aspects of these devices and the klystron, is a device called a Twicetron.

Magnetron

Magnetrons are used to produce microwaves.

This is the original device used for production of microwaves and was invented during the Second World War for use in RADAR equipment.

Magnetrons work using a principle known as velocity modulation.

A circular chamber, containing the cathode, is surrounded by and connected to a number of resonant cavities. The walls of the chamber are the anode. The cavity dimensions determine the frequency of the output signal. A strong magnetic field is passed through the chamber, produced by a powerful magnet. The cathode is different from most thermionic valves in that there is no heater element. i.e. a cold cathode.

Naturally excited electrons on the surface of the cathode are drawn off, into the chamber, toward the outer walls or anode. As the electrons move out, they pass through a magnetic field that produces a force perpendicular to the direction of motion and direction of the magnetic field. The faster the electrons move, the more sideways force is produced. The result is that the electrons rotate around the central cathode as they move toward the outside of the chamber.

As electrons move past the entrances to the resonant cavities a disturbance is made to the electro magnetic (EM) field that is at rest in the cavities. The cavity begins to oscillate. When another electron moves past the cavities, it also interacts with the internal EM field. The motion of the electron can be slowed or sped up by the cavity field. As more electrons interact with the cavity EM fields, the internal cavity oscillations increase and the effect on the passing electrons is more pronounced.

Eventually, bands of electrons rotating together develop within the central chamber. Any electrons that fall behind a band are given a kick by the resonant cavity fields. Any electrons going too fast have their excess energy absorbed by the cavities. This is the velocity modulation effect. The frequency of the resonance and electron interaction is in the order of GHz. (10^9 cycles per second)

In order to have a signal output from the magnetron, one of the cavities is taped with a slot or a probe to direct energy out into a waveguide for distribution.

Magnetrons for RADARs are pulsed with short duration and high current. Magnetrons for microwave ovens are driven with a continuous lower current.

The magnetrons for WWII bombers, operated by the RAF, were sometimes taped into a shielded box so that the aircrew could heat their in-flight meals, hence the first microwave ovens.

Cathode Ray Tube

A cathode ray tube or CRT is a specialized vacuum tube in which images are produced when an electron beam strikes a phosphorescent surface. Television sets, computers, automated teller machines, video game machines, video cameras, monitors, oscilloscopes and radar displays all contain cathode-ray tubes. Phosphor screens using multiple beams of electrons have allowed CRTs to display millions of colors.

The first cathode ray tube scanning device was invented by the German scientist Karl Ferdinand Braun in 1897. Braun introduced a CRT with a fluorescent screen, known as the cathode ray oscilloscope. The screen would emit a visible light when struck by a beam of electrons.

The History of the Cathode Ray Tube

TV Tubes

TV tubes are basically Cathode Ray Tubes. An electron beam is produced by an elecrically-heated filament, and that beam is guided by 2 Magnetic fields to a particular spot on the Screen. The beam is moved so very quickly, that the eye can see not just one particular spot, but all the spots on the screen at once, forming a variable picture.

> Colours are produced by having 3 or more differently coloured screen spots activated at once to a variable degree.

The 2 magnetic fields are one for the vertical deflection, one for the horizontal deflection, and they are provided to the beam by external coils.

Oscilloscope Tubes

Oscilloscope tubes are basically the same as TV tubes, but the beam is guided by 2 Electrostatic fields provided by internal pieces of metal. It is a necessity because an oscilloscope uses a very large range of synchronisation frequencies for the deflection, when a TV set uses fixed frequencies, and it would be too difficult to drive large coils on a so large band of frequency. They are much deeper for the same screen size as a TV tube because the deflection angle is little. A TV tube has a deflection angle of 90° for the better one, 120° for the other, and an oscilloscope tube has a deflection angle of around 20°.

Cathode ray tube

Amplifying Tubes

These have been superseded by Solid State Devices. The electron beam, coming from the electrically heated filament at the Cathode, passes via one or more "grids", that, depending on their particular voltage, can weaken or strengthen the beam. A small change of voltage on the grid causes a large change of voltage on the Anode.

> Many kinds of Ampliying tubes exist, used for different purposes, such as causing Oscillations.

X-Ray Tubes

These are used for medical purposes. They produce a beam that penetrates the patient's body, and is then used to more or less activate a photographic film showing, for example, broken bones. X-Rays can be dangerous, and exposure to them is therefore limited by suitable lead barriers and clothing.

Other Cathode Ray Tubes

During World War II "Electrolocation", or "Radar", was very important in locating the direction, distance and altitude of enemy aircraft. The green or yellow screen on Cathode Ray Tubes showed to operators, in terms of distance on the screen, the time between sending out a beam, and its reflected return. The angle of the rotating antenna was shown on the screen as azimuth.

External Links

Wikipedia: Vacuum tube Vacuum tubes on Wikipedia

Basics of vacuum tubes German and US vacuum tubes theory.

Diodes

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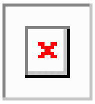
Diode

Theoretically, a diode allows current flow in only one direction. An ideal diode acts as a perfect insulator for currents flowing in one direction and as a perfect conductor for currents flowing through it in the other direction. The direction in which the diode allows current to flow is called the forward bias direction and that in which current is resisted is called reverse bias direction. Diode has a symbol as shown



Construction

The modern semiconductor diode consists of two regions of semiconductor each having impurities of different types such that one side has excess holes (p-region) and the other has excess electrons (n-region). Such a junction of p and n regions is called a pn junction diode. The p-region has about twice as much area as the n-region to compensate for the lesser mobility of holes compared to electrons.

> + o-- [P | N]--o - .Theoretically, a diode allows current flow in only one direction

Operation

I V Curve

As seen in the graph above the diode actually works in both the forward region and the backward region. In the forward region the value of I and V are positive and in the backward region I and V are negative.

Forward Region

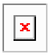
Current and Voltage are positive

When $V < V_d$. $I = 0$. Diode does not conduct

Khi $V = V_d$. $I = 1mA$. Diode starts to conduct . $V_d = 0.3v|Ge , 0.6v|Si$

V_d is called Forward Break Over Voltage

Khi $V > V_d$. Diode conducts current . Current is calculated by



]

Backward Region

Current and Voltage are Negative

When the value of voltage is more negative than the Peak Inverse Voltage (PIV) Voltage the Diode will be destroyed

Ideal Diode

The real diode approaches the ideal diode in the sense that the reverse current is extremely small (less than 1fA) at least for a significant part of the characteristic, and the forward current is very high (on the order of 1mA). Although a real diode does not have the characteristics as the ideal diode, in theory it is possible to make an ideal diode if the concentrations of dopants in both the regions are infinite. However, there is no way of actually doing this and experiments do not agree.

The Shockley equation

The diode reverse (*saturation*) current is governed by the doping concentration. The current flowing through the device varies as the voltage applied across it changes as given by the Shockley diode equation (not to be confused with Schottky):

In the equation above

is defined as

, where

is Boltzmann's constant,

is the temperature in Kelvin, and

is the magnitude of the charge on an electron.

In the forward bias direction, current flows with low voltage. If one draws a characteristic for this equation, a sharp increase in current can be seen at a particular voltage called the *cut-in voltage* or the *on-voltage*.

In the reverse bias mode, the diode current is approximately

. This is called the reverse *saturation* current because it looks like the diode is saturated with charge and cannot allow more current in the reverse bias direction than this.

Break-down

However, a break from the above equation takes place at a point called *break-down voltage*. One could think of it as the point where the Shockley equation *breaks down* and is no longer valid. There are two reasons for breakdown to occur.

Avalanche Breakdown

This occurs as a result of excess minority carriers in a region. Minority carriers are those carriers that are in the wrong region. For example, electrons will be minority carriers in the p-region.

Zener Breakdown

This is basically due to a size difference or dopant concentration difference. One of the regions has a greater region of depletion (Reverse bias voltage induces a depletion region, which is sparse in a densely doped region and dense in a sparsely doped region.)

See also Zener diodes

Summary

So basically, there are three modes in which a diode operates:

Forward

No current flows until a small forward voltage is reached called *cut-in* voltage.

Reverse

The diode prevents current from flowing in the opposite direction. Current is small, and voltage can be large (but not exceeding the Zener voltage.)

Breakdown

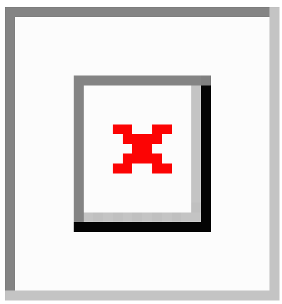
Once the diode voltage is more negative than the Zener voltage, the diode allows current to flow in the reverse direction.

When there is no voltage applied, the excess electrons of the N type semiconductor flow into the holes of the P type semiconductor. This creates a depletion region that acts as a voltage.

Diode Variations

Bridge Rectifier:

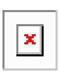
A diode circuit that 'rectifies' alternating current (AC) into direct current (DC). The bridge rectifier is a full-wave rectifier, meaning that both the positive and negative portions of the wave become positive. (In a half-wave rectifier, positive stays positive, and negative becomes zero.) The bridge rectifier has advantages over other full-wave rectifier designs, because it reduces peak-inverse voltage (PIV), the largest negative voltage across a single junction diode. By reducing the PIV, it becomes possible to use diodes with lower breakdown (Zener) voltages. This allows the use of cheaper diodes to perform the same function.



A bridge rectifier shown as 4 discrete diodes.

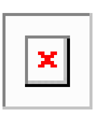
LED (Light Emitting Diode)

A diode that emits light!



Schottky:

A diode made from a metal-semiconductor junction, rather than an p-type/n-type silicon junction. These diodes typically have a much lower forward voltage drop than standard diodes (around 0.2V versus 0.6V).



Zener:

A diode that is meant to be operated in the breakdown region. These diodes have lower Zener (breakdown) voltages, so that they can achieve the breakdown mode without melting. Unlike other diodes, these have very specific breakdown voltages, typically between 2 and 200 volts. See also Zener diodes

Transistors

Electronics | Foreword | Basic Electronics | Complex Electronics | Electricity | Machines | History of Electronics | Appendix | edit

Transistor

A transistor is a Solid State Device made by joining three positive-type and negative-type semiconductors together. In general, all transistors have three pins: base, collector, and emitter. Transistor is a bi-polar device that is transistor has two junctions namely BE and CE.

Construction

A lightly doped region called base is sandwiched between two regions called the emitter and collector respectively. The collector handles large quantities of current, hence its dopant concentration is the highest. The emitter's dopant concentration is slightly lesser, but its area is larger to provide for more current than the collector. The collector region should be heavily doped because electron-hole pairs recombine in that region, while the emitter is not such a region. We can have two varieties in this kind of transistor.

NPN Transistor

NPN made from joining one positive-type semiconductor in between two negative-type semiconductors. Here a lightly doped p-type semiconductor (semiconductor with more holes than electrons) is sandwiched between two well-doped n-type regions. It is like two pn-junctions facing away. An IEEE symbol for the NPN transistor is shown here. The arrow between the base and emitter is in the same direction as current flowing between the base-emitter junction. Power dissipated in the transistor is

, where

is the voltage between the collector and the emitter and

is the collector current.

PNP Transistor

PNP Transistor made by sandwiching a Nagative-Typed semiconductor in between two Positive-Typed semiconductors.

Transistor Operation

Amplifier

Transistor conducts current when Base Voltage is greater than BE junction's voltage. Current is non zero.

$I_B \neq 0$

$I_E = \alpha\ I_B$

$I_C = \beta\ I_B$

Switch

The characteristic that Transistor conduct or non conduct current make transistor suitable for Electronic Switching. Transistor conducts current when Base Voltage is greater than BE junction's voltage. Current is non zero. This correspond to a Closed Switch. Transistor does not conduct current when Base Voltage is less than BE junction's voltage. Current is zero. This correspond to a Opened Switch.

External links

Wikipedia:Transistor

FET

Field Effect Transistor

The most common transistors today are FETs (Field Effect Transistor). These transistors are characterized as having a conductance between source and drain dependent on the voltage applied between the gate and the source terminals. The dependence is linear if the gate to drain voltage is also high along with the gate to source voltage. It turns into a square-law relationship if the gate to drain voltage is not enough.

Current Voltage Characteristics

Disadvantages

One of the issues that comes up in circuit design is that as chips get smaller the insulator gets thinner and it starts to look like Swiss cheese. As a result the insulator starts acting like a conductor. This is known as leakage current. One solution is to replace the insulator by a material with a higher dielectric coefficent.

Two types: enhancement and depletion. Enhancement is the standard MOSFET, in which a channel must be induced by applying voltage. Depletion MOSFETs have the channel implanted, and applying voltage causes the channel to cease being conductive.

FET transistors respond to the difference in voltage bias between the gate and the source.

MOSFET (Metal-Oxide-Semiconductor FET): standard FET

JFET (Junction Fet): When voltage is applied between the source and drain current flows. Current only stops flowing when a voltage is applied to the gate.

MESFET (MEtal-Semiconductor FET): p-n junction is replaced with Scottky junction. Not made with Silicon.

HEMT (High Electron Mobility Transfer): A MESFET

PHEMT (Pseudomorphic HEMT):

MOSFET

Complementary Metal Oxide Semiconductor

CMOS , Complementary Metal Oxide Semiconductor is not a type of transistor. It is a logic family, based on MOS transistors.

Construction & Operation

CMOS is made of two FETs blocking the positive and negative voltages. Since only one FET can be on at a time, CMOS consumes negligible power during any of the logic states. But when a transition between states occurs, power is consumed by the device. This power consumed is of two types.

Short-circuit power

For a very short duration, both transistors are on and a very huge current flows through the device for that duration. This current accounts for about 10% of the total power consumed by the CMOS.

Dynamic power

This is due to charge stored on the parasitic capacitance of the output node of the device. This parasitic capacitance depends on the wire's area, and closeness to other layers of metal in the IC, besides the relative permittivity of the quartz layer separating consecutive metal layers. It also depends (to a much smaller extent) upon the *input capacitance* of the next logic gate. This capacitance delays the rise in the output voltage and hence the rise or fall in the output of a gate is more like a that in a resistor-capacitor (RC) network. Thus the dynamic power consumed due to switching action in one gate is given by:

Amplifiers

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Types of Amplifiers

Amplifier are generally put in four categories

1. voltage,
2. current,
3. transresistance and
4. transconductance.

The model for a voltage amplifier is shown in figure 1. Real amplifiers have input and output resistance. This is reflected in the model.

Figure 1: A Voltage Amplifier.

Gain

Gain is the increase in the strength of a signal and is often expressed in decibels (dB). An increase of 3 dB is about equal to doubling in a linear scale. A gain of more than 1 is called amplification, while a gain of less than 1 is called Attenuation.

Gain is given different symbols depending of the type. For No load gains

Voltage gain is A_{vo},

Current gain A_{io},

Transconductance G_m

Transresistance R_m.

Using the model, the gain with a load can be calculated.

Transistor amplifiers

Common Emitter

QUALITATIVE CHARACTERISTICS

- Current Gain: ..... HIGH
- Voltage Gain: ..... HIGH
- Power Gain: ..... HIGH
- Input Impedance: ... AVERAGE
- Output Impedance:... AVERAGE

```
QUANTITATIVE CHARACTERISTICS

Input Resistance(base): Zb=β×re'

-> β: Current Gain (Ic/Ib), where 'Ic' is Colector DC current and 'Ib' is DC Base cur-
rent;
-> re': Base-Emitter dynamic resistor (Ut/Ie), where Ut is thermal voltage(≈25mV at
25°C) and
'Ie' is DC emitter current;

Input Resistance(general): Zg= Zb || R1 || R2, where R1 and R2 are the same as the
picture above.
```

Common Collector

```
QUALITATIVE CHARACTERISTICS

Current Gain: ..... HIGH
Voltage Gain: ..... ≈1
Power Gain:   ..... LOW
Input Resistance: ... HIGH
Output Resistance:... LOW
```

Common Base

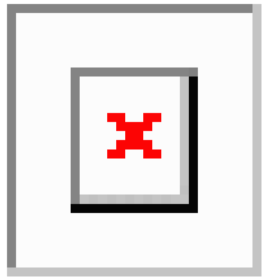
```
QUALITATIVE CHARACTERISTICS

Current Gain: ..... ≈1
Voltage Gain: ..... HIGH
Power Gain:   ..... AVERAGE
Input Resistance: ... LOW
Output Resistance:... HIGH
```

FET Configurations

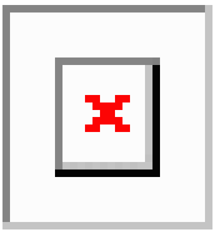
As with BJT configurations, there are three FET configurations, each one corresponding to one of the terminals of the transistor.

Common Source



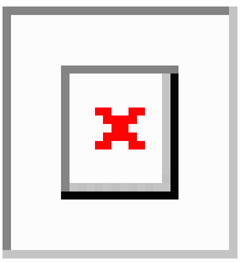
Common Source Amplifier

Common Drain



Common Drain Amplifier

Common Gate



Common Gate Amplifier

Biased Voltage Class

Transistors may be biased in a variety of classes. A trade off of linearity and power consumption is usually made where a Class A

Class A

The transistor is "on" all the time. We say 360 degrees of conduction, representing an entire period of the sine waveform. Ideally, this class produces very little distortion, however consumes a lot of power and is also least preferred.

This is the most linear of the classes, meaning the output signal is a truer representation of what was imputed. Here are the characteristics of the class: 1.The output device (transistor) conducts electricity for the entire cycle of input signal. In other words, they reproduce the entire waveform in its entirety. 2.These amps run hot, as the transistors in the power amp are on and running at full power all the time. 3.There is no condition where the transistor(s) is/are turned off. That doesn't mean that the amplifier is never or can never be turned off; it means the transistors doing the work inside the amplifier have a constant flow of electricity through them. This constant signal is called "bias". 4.Class A is the most inefficient of all power amplifier designs, averaging only around 20%.

Because of the way they are usually designed, Class A amplifiers are very inefficient. They do not need to be built in this way, but for every watt of output power, they can typically waste 4-5 watts as heat. They are usually very large, heavy and because of the 4-5 watts of heat energy released per watt of output, they run very hot, needing lots of ventilation (not at all ideal for a car, and rarely acceptable in a home). This is not due to the amplifier type, but the fact that even many design engineers do not fully understand how they work and often copy their designs from previous ones. The upside is that these amps are the most enjoyed of all amplifiers. When properly designed, the Class A amp gives the best representation of musical detail, with no clipping of the waveform. As a result the sound is cleaner and more linear; that is, it contains much lower levels of distortion.

They are the most accurate of all amps available, but at greater cost to manufacture, calling for tight tolerances and additional components for cooling and heat regulation.

[The reference to poor design can be related directly to the U.S. quality of education. As of the 2001 survey, the U.S. education system was 18th on the list of the top 24 industrialized nations. This applies in turn to all types of education. Ref: http://www.cbsnews.com/stories/2002/11/26/world/main530872.shtml "U.S. now ranks 25th in math, 17th in science, and 14th in reading out of the 34 Organization for Economic Cooperation and Development (OECD) countries" http://abcnews.go.com/Politics/china-debuts-top-international-education-rankings/story?id=12336108]

Class AB

The transistor is "on" for slightly more than half the cycle (>180 degrees) of a sine wave and is the most common configuration used in push-pull audio power amplifiers. In push-pull amplifiers, Class AB produces mostly odd order distortion, however it is far more power efficient than Class A. Odd order distortion is not considered pleasing to hear in audio power amplifiers. This distortion can easily be removed with the addition of a simple negative feedback loop into the system as shown by the diagram below:

This type of amplifier is extremely easy to build and is the industry standard for audio amplifiers.

Issues with this type of amplifier include poor efficiency, size and cost. A typical class ab amplifier will have a power efficiency of 40-80%. Because of this they require large heat sinks to cool the transistors, this also increases the cost of the amplifier due to the extra material to create these heat sinks.

This is the compromise of the bunch. Class AB operation has some of the best advantages of both Class A and Class B built-in. Its main benefits are sound quality comparable to that of Class A and efficiency similar to that of Class B. Most modern amp designs employ this topology.

Its main characteristics are: In fact, many Class AB amps operate in Class A at lower output levels, again giving the best of both worlds The output bias is set so that current flows in a specific output device for more than a half the signal cycle but less than the entire cycle. There is enough current flowing through each device to keep it operating so they respond instantly to input voltage demands. In the push-pull output stage, there is some overlap as each output device assists the other during the short transition, or crossover period from the positive to the negative half of the signal.

There are many implementations of the Class AB design. A benefit is that the inherent non-linearity of Class B designs is almost totally eliminated, while avoiding the heat-generating and wasteful inefficiencies of the Class A design. And as stated before, at some output levels, Class AB amps operate in Class A. It is this combination of good efficiency (around 50) with excellent linearity that makes class AB the most popular audio amplifier design.

There are quite a few excellent Class AB amps available. This is the design I recommended for most general-use applications in home and car. Usually, parts choice rivals that of Class A amps, and dollar for dollar these are some of the best values in stereo amplification. There can be some variation in design principle, but generally these are well-designed amps since their function is very well-understood by audio designers.

Class B

The transistor is "on" for only half the cycle (exactly 180 degrees) of a sine wave and is also very typically used in push-pull amplifier circuits. Ideally this class produces mostly odd order distortion. In audio applications it is believed that odd order distortion is not pleasing to hear. It is difficult to build a low distortion Class B amplifier and hence Class AB is almost universal.

In this amp, the positive and negative halves of the signal are dealt with by different parts of the circuit. The output devices continually switch on and off. Class B operation has the following characteristics: The input signal has to be a lot larger in order to drive the transistor appropriately. This is almost the opposite of Class A operation There have to be at least two output devices with this type of amp. This output stage employs two output devices so that each side amplifies each half of the waveform. [li Either both output devices are never allowed to be on at the same time, or the bias (remember, that trickle of electricity?) for each device is set so that current flow in one output device is zero when not presented with an input signal. Each output device is on for exactly one half of a complete signal cycle.

These amps run cooler than Class A amps, but the sound quality is not as pure, as there is a lot of "crossover" distortion, as one output device turns off and the other turns on over each signal cycle.

This type of amplifier design, or topology, gives us the term "push-pull," as this describes the tandem of output devices that deliver the audio signal to your speakers: one device pushes the signal, the other pulls the signal. They can be less expensive, because one can use two cheap output devices instead of one high-quality one in the design.

As I mentioned before, the input signal has to be lot larger, meaning that from the amplifier input, it needs to be "stepped up" in a gain stage, so that the signal will allow the output transistors to operate more efficiently within their designed specifications. This means more circuitry in the path of your signal, degrading sound even before it gets to the output stage

Class C

The transistor is "on" less than half the cycle of a sine wave. We say <180 of conduction. This class produces both even and odd order distortion, however is very efficient.

Class D

The class D amp has been developed after the short-comings of past generations, including classes A, B, AB, and C. Many people mistake the D as standing for digital. Although it is a “switching” amp, meaning it turns “on” and “off” at a specific frequency, it is a wrong assumption. D was simply the next letter in the alphabet. Consuming the least power out of its previous generations, the class D amps are generally smaller, making them ideal for mobile devices. It is because of their power efficiency, small size, and cheaper costs that the class D amps are quickly becoming the new industry standard for audio electronic. Companies such as Advanced Analog, Texas Instruments as well as other companies have released 50W stereo class d amplifiers that are the size of a penny and did not require any sort of heat sinking, something that was not possible with other types of amplifiers.

The basic design includes two MOSFET transistors in series, one pFET and one nFET being driven by a pulse width modulated (PWM) signal. Because of the properties of MOSFET transistors they are either fully on or fully off. When the transistor is off and the current is zero (so the amount of power wasted heating up the transistor is zero), or the transistor is fully on and the voltage across it is very close to zero (so the amount of power wasted heating up the transistor is again, very close to zero).

Because an analog signal needs to be transformed into a PWM signal a certain amount of distortion can occur, but the amount of distortion can be minimized. Because a PWM signal is very much like a digital signal, the sampling theorem states that if the sampling frequency is more than half the maximum frequency of the source it can be reproduced exactly. For audio signals the maximum frequency heard by humans is roughly 20kHz, so a PWM generator would only need to provide a minimum switching frequency of 40kHz. Because of the availability of faster components many class d amplifier designers will use switching frequencies closer to 400kHz to further reduce the distortion.

Issues of concern with a class d amplifier include electromagnetic emissions. Due to the presence of a medium frequency signal in the circuit, steps must be taken to reduce the emission of these signals that could interfere with other electronic devices.

==== Class E ==== (oops, class D again?) Switching amplifier These amplifiers are erroneously called "digital" amplifiers by the press and many audio "experts." Here's the skinny on Class D: While some Class D amps do run in true digital mode, using coherent binary data, most do not. They are better termed "switching" amplifiers, because here the output devices are rapidly switched on and off at least twice for each cycle. Depending on their switching frequency, they may be "switched on" or "off" millions of times a second. Class D operation is theoretically 100% efficient, but in practice, they are closer to 80-90% efficiency. This efficiency gain is at the cost of high-fidelity.

Think of Class D amps as being similar to a switchable power supply, but with audio signals controlling, or modulating, the switching action. To do this, you use a technology called Pulse Width Modulation (or PWM, a technology found in many CD players).

According to experts, audio signals can be used to modulate a PWM system to create a high power audio amplifier at fairly low voltages using very small components. Class D audio uses a fixed, high frequency signal having pulses that vary in width based on input signal amplitude. So, for example, a deep bass note creates a large pulse in the carrier signal. This can be translated into a musical signal by the on/off nature of the output devices.

Class D amplifiers are generally used for non-high-fidelity, or subwoofer applications.

There is a fifth (and, nominally, a sixth) class of amplifier, but they are rarely seen in practice in the consumer market. One is the Class G and the other Class H. These are similar in design to Class AB topologies, but both feature two power supplies that switch on or off, depending on the musical signal imputed. Using two power supplies improves efficiency enough to allow significantly more power for a given size and weight. Class G is becoming common for pro audio designs. Class H amps are designed to use the same topology as Class G, but it provides just enough voltage for optimum operation of the output devices. Again, its an attempt to increase efficiency, but at the expense of fidelity ultimately.

Class F

Class S

Amplifier

Operational amplifiers

Electronics/Operational amplifiers

Analog multipliers

Analog multipliers

An analog multiplier is a circuit with an output that is proportional to the product of two inputs:

where K is a constant value whose dimension is the inverse of a voltage. In general we might expect that the two inputs can be both positive or negative, and so can be the output. Anyway, most of the implementations work only if both inputs are strictly positive: this is not such a limit because we can shift the input and the output in order to have a core working only with positive signals but external interfaces working with any polarity (within certain limits according to the particular configuration).

Two possible implementations will be shown. Both will be using operational amplifiers, but the first one will use diodes to get the needed relationships, the second one MOSFET transistors.

Diode Implementations

As known, using operational amplifiers and diodes it's quite easy to obtain the logarithm and the exponential of a certain input. Remembering the property of logarithms:

we can multiply two signals first calculating their logarithm, then summing them and finally calculating the exponential of such a sum. From the point of view of mathematics, such an approach works as long as the two inputs are positive, because the logarithm of a negative number does not exist (in the real domain). We'll see that this limit is valid for the actual circuit as well, even if the reason will be more "physical". The block diagram of this implementation is the following:

If we simply append the circuits for logarithm, sum and exponential we get the following configuration:

for a quick overview on the behavior of the circuit, we'll assume that all the resistors *R* have the same value. It is obviously possible to use different values to get different results, but we will not consider it here. Let us use the following notation for the relationship between current and voltage on a diode:

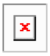
where

is the threshold voltage and I_s is the current flowing through the diode if it's inverse-polarized. If we analyze the circuit without introducing any approximation we get:

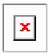
so the final output is:

as it is clear, in the output there is the multiplication we were looking for, but there is another term we don't want. It can't be simply considered an error because it might be as great as the multiplication element, so it has to be removed. Anyway this is an easy task, since it is necessary only to add another stage to sum exactly

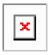
, so we will have no error. The complete multiplier circuit is the following:



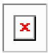
where the output voltage is given by:



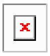
that's exactly what we wanted. The circuit works as long as the following relationship is verified:



so the inputs can be zero or sightly negative but, since



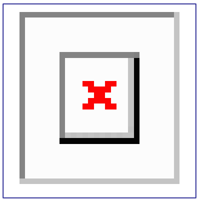
will be a small voltage, we are allowed to rewrite the relation simply as



. From the mathematical point of view this is due to the fact that we can't calculate the logarithm of a negative number, from a physical point of view the limit is due to the fact that we can obtain only very small currents (almost zero) inverse-polarizing the diodes.

In practical applications, the diodes are replaced with BJTs connected so to work like a diode.

MOS implementation



Since it is possible to use a MOSFET transistor as a voltage controlled resistor, we can use this feature to create an analog multiplier. Let us refer to picture on the right. With the letter we indicate the different pins: **D**rain, **S**ource and **G**ate. MOS are symmetrical devices, so we could replace the drain with the source without affecting the behavior of the device. Anyway we'll call *source* the lowest voltage pin and *drain* the point with the highest voltage. When the voltage between gate and source is less than the voltage between drain and source, i.e.

, the relationship between current and voltage is the following:

assuming we can always use this relationship, the analog multiplier configuration is the following:

where source and drain of both devices are pointed out. If

and

are positive, then the sources will remain there because that points are virtually connected to ground by the operational amplifiers. The current flowing through

is defined: one side of the resistor has the voltage

, the other one is grounded. That same current will flow through the MOS

, thus defining the voltage

. The current is given by:

but

and

. replacing and calculating we get:

considering the other MOS

we have:

where

and

. Replacing we get:

from which we finally get the output voltage:

and this is what we wanted. The difference between the previous configurations are:

- the MOS implementation is simpler and requires fewer devices
- in the calculations for the diode configuration we did not introduce any approximation, while the MOS configuration we did.

In other words, the diode implementation is more complicated but it works fine for a wider range on inputs.

Chapter 4: Digital Circuits

Digital Circuits

Overview

In Digital circuits there are two parts one is Digital the other is circuits.

Digital

means a description of system which operates on digits or numbers.

The numbers that a digital system operates upon are binary numbers.One binary digit just have two values '0' and '1'. This '0' or '1' are analogous to 'off' and 'on', 'false' and 'true', etc. The Binary digIT is known as 'bit'. In day to day activities we use numbers and every digit of that number can be between 0 - 9. We use combination of such digital to for numbers bigger than 9. Similarly we can use combination of bits, i.e. combination of 1 & 0, to form bigger binary numbers.

Circuit can be any electric circuit and Digital circuit is a circuit which is designed to implement the description of digital circuit.

Digital circuits are developed using a special type of mathematics called 'Boolean Algebra'.

Boolean Algebra

Boolean Algebra

Boolean Algebra was created by George Boole (1815 - 1864) in his paper *An Investigation of the Laws of Thought, on Which Are Founded the Mathematical Theories of Logic and Probabilities*, published in 1854. It had few applications at the time, but eventually scientists and engineers realized that his system could be used to create efficient computer logic. The Boolean system has two states: **True** (T) or **False** (F). This can be represented in several different ways as on or off, one or zero, yes or no, etc. These states are manipulated by three fundamental operations called *logical operators*: **AND**, **OR** and **NOT**. These operators take certain inputs and produce an output based on a predetermined table of results. For example, the AND operator takes two (or more) inputs and returns an 'on' result only when both (or all) inputs are 'on'.

- In these tables T means "True", or "Yes", or 1 (in electronics), and
- F means "False", or "No" or 0 (in electronics).
- For example, the 1st line of the AND table says that if A is F and B is F then the result also is F. This is also said often as If A is 0 and B is also 0, then A AND B = 0 times 0 = 0
- Also at the bottom of the AND table 1 times 1 is 1.
- Looking at the OR table, use plus instead of times: 0 plus 0 is 0, where again 0 is F and 1 is T. Only 0 and 1 exist, therefore if the result of the addition is more than 1, then change it to 1.
- The 3rd table shows NEGATION: whatever it is, change it to the other; 0 is changed into 1, and 1 is changed into 0.

Truth Tables

AND

A	**B**	
F	F	F
F	T	F
T	F	F
T	T	T

OR

A	**B**	
F	F	F
F	T	T
T	F	T
T	T	T

NOT

A	
F	T
T	F

These simple operators are good because they allow us to create very simple logic circuits: if user put in a quarter AND the Coke button is pressed, drop a Coke

There are ways, however, to combine these expressions to make much more complex but useful digital circuits. By using multiple operators on the same inputs, it is possible to create much more complex outputs. An expression like: A and B or C would have a truth table of the following:

A and B or C

A	B	C	X
0	0	0	0
0	0	1	1
0	1	0	0
0	1	1	1
1	0	0	0
1	0	1	1
1	1	0	1
1	1	1	1

This truth table follows the rules If A and B are true, or C is true, then X is true

Exercise: Go through each case in the table and check it using the above statement.

Formal Mathematical Operators

AND is represented by

or

that is A AND B would be

or

.

OR is represented by

or

that is A OR B would be

and

.

NOT is represented by

or

that is NOT A is

or

.

If these three operators are combined then the NOR and NAND can be created. So A NOR B is

or

. NAND is

or

. Other notations are valid as well, and many different combinations of them arise in mathematics and engineering. No universal standard has been agreed upon. However, most sources will make explicit the particular notation used.

Boolean Algebra Laws

Boolean Algebra, like regular algebra, has certain rules. These rules are Associativity, Distributivity, Commutativity and De Morgan's Laws. Associativity, Commutativity and Distributivity only apply to the AND and OR operators. Some of these laws may seem trivial in normal Algebra but in other algebras they are not.

Associativity

Associativity is the property of algebra that the order of evaluation of the terms is immaterial.

Or

Wikipedia:Associativity

Distributivity

Distibutivity is the property that an operator can be applied to the terms within the brackets.

Or

Wikipedia:Distributivity

Commutativity

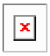
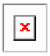
Commutativity is the property that order of application of an operator is immaterial.

Or

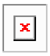
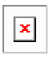
Wikipedia:Commutativity

De Morgan's Law

De Morgan's Law is a consequence of the fact that the not or negation operator is not distributive.

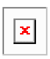



Or

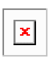



Notes

It is important to note that



Or



This can be seen as either AND having a higher precedence or the fact that Associativity does not hold between AND and OR or that it is an invalid application of distributivity.

Another way of looking at this is the possible application of our understanding of normal algebra rules using the second notation. Where clearly the analogy between OR being addition and AND being multiplication is made. We would never make this error if this were high school algebra.

Rules

All of these Laws Result in a number of rules used for the reduction of Boolean Algebra.

1.
2.
3.
4.
5.
6.
7.
8.
9.
10.
11.

Or

1.
2.
3.
4.
5.
6.

7.
8.
9.
10.
11.

Examples

Simplify the following Expressions.

1.
2.

Or

1.
2.

For number 1 using rule 7. We get.

Or

Which happens to be rule 5 so the answer is zero. In number 2 we can take out A. Given

Or

The Expression within brackets is rule 8. So the answer is A.

See also

Wikipedia: Boolean logic

TTL

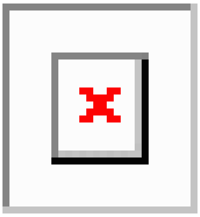
Electronics | Foreword | Basic Electronics | Complex Electronics | Electricity | Machines | History of Electronics | Appendix | edit

Introduction

TTL stands for **Transistor-Transistor Logic**. It is the system based on combining transistors in such a way that they can be used for logic gates. Transistors have the capability of becoming parts of very complex devices when combined. An average microprocessor uses upwards of 40 million transistors. Transistors in microprocessors, however, are microscopic as opposed to the discrete components used in consumer electronics and circuit-boards.

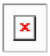
The NOT Gate

The NOT gate works by inverting the input. The TTL version of the NOT gate contains one transistor, seen below:



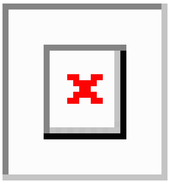
When the input, A, is **high** (+5V), the base of the transistor is saturated, allowing current to flow from the collector of the transistor to the emitter. Since this is possible, the current does not take the higher resistance path through the output (assuming it has a resistive load attached to it such as an LED). When the input is **low** (0V), the current has no choice but to flow out of the inverted A output (the A with the line overtop to indicate it is negated). The two resistors in the circuit are for limiting current as to not destroy the transistor, and sometimes may not even be required depending on the transistor.

(note: this image is considered *Resistor-Transistor Logic* The proper TTL representation is below.)

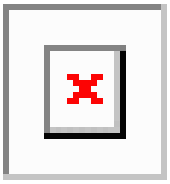


TTL Inverter (NOT Gate)

To further explain, the NOT gate has been integrated into a circuit by connecting it to a current probe and a battery. When the switch for the input of the not gate is not hit, the current flows in the path indicated by the red diagram below. The current flows through the resistor because the transistor does not conduct when the base is not saturated.:



However, when the switch is hit, making the input **high**, the circuit is shorted and current flows directly from one terminal of the battery through the transistor, to the other terminal. This is illustrated further in the next figure:



In real logic gates, several more transistors are used in order to stabilize the input and output. Although this may seem like a large hike in complexity and price, creating transistors in ICs is a lot cheaper and easier to do, as they do not have to even have a shell or casing, and are a lot smaller.

CMOS

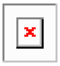
CMOS

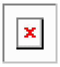
CMOS stands for **C**omplementary **M**etal-**O**xide-**S**emiconductor. Metal-Oxide-Semiconductor refers to the construction method of the component Field-Effect Transistors (MOSFETs), and Complementary means that CMOS uses both n-type (nMOS) and p-type (pMOS) transistors. Older designs had used only n-type transistors, and are referred to as NMOS logic.

n-type MOSFETs are active (conductive) when their input voltage is high, while p-type MOSFETs are active when their input voltage is low.

All CMOS gates are arranged in two parts: the pull-up network (PUN), built from p-type transistors and connect to source; and the pull-down network (PDN), built from n-type transistors and connected to ground (also called drain). The two parts are logical duals of each other, so that if the PUN is active, then the PDN is inactive, and vice-versa. In this way there can never be a direct path between source and ground (in any steady state).

The biggest advantage of CMOS over NMOS is that CMOS has a rapid change from both hi-to-low and from low-to-hi. NMOS transitions only slowly from low-to-hi (because it uses a resistor in place of a PUN), and since overall circuit speed must take into account the worst case, NMOS circuits must be much slower.





Logic Gates

NOT

The simplest CMOS circuit: the NOT gate, or inverter. Although uncomplicated, it demonstrates the basic structure of a CMOS gate; a series of inputs (in this case, one) which are connected to the transistors, the PUN (consisting of a single p-type transistor) connected to source, the PDN (consisting of a single n-type transistor) connected to ground, and the output which is fed from both the PUN and PDN.

When the input voltage is high, the p-type transistor will be inactive, and the n-type transistor will be active. This creates a connection between ground and the gate output, pulling the gate's output to low. Conversely, when the input voltage is low, the p-type transistor will be active instead, creating a connection between the output and source, pulling the gate's output to high.

Input	Output
0	1
1	0

NAND

The PUN for NAND consists of a pair of p-type transistors in parallel, one with the A input feeding it and one with the B input feeding it. Therefore the PUN is active, and the output of the gate is high, as long as either of these inputs is low.

The PDN for NAND consists of a pair of n-type transistors in series, also each fed by one of the two inputs. Therefore the PDN is active, and the output of the gate is low, only if both of the inputs are high.it uses the logic a bar(OR)b bar

Input 1	Input 2	Output
0	0	1
0	1	1
1	0	1
1	1	0

AND

A CMOS AND gate is constructed by driving a NOT gate from the output of a NAND gate.

Input 1	Input 2	Output
0	0	0
0	1	0
1	0	0
1	1	1

NOR

"Upside down" relative to the NAND gate, the NOR gate is made from a PUN of two p-type transistors in series and a PDN of two n-type transistors in parallel.

Input 1	Input 2	Output
0	0	1
0	1	0
1	0	0
1	1	0

OR

As AND is to NAND, OR is to NOR. CMOS OR is constructed by feeding the output of NOR to a NOT gate.

Input 1	Input 2	Output
0	0	0
0	1	1
1	0	1
1	1	1

XNOR

To build an XNOR gate, first we will need easy access to the inverted inputs. This is accomplished with a pair of NOT gates. The original inputs are A and B, and their inverted forms we will call NOT-A and NOT-B. Both the PUN and PDN are made of four of the appropriate type of transistor, in two parallel sets, of series of two transistors each. In the PUN there is one series fed by A and B and the other is fed by NOT-A and NOT-B; in the PDN one series is fed by A and NOT-B and the other is fed by NOT-A and B.

All told, this takes 12 transistors (4 in the PUN, 4 in the PDN, and 2 for each inverter). There are more efficient designs for the XNOR circuit, but they require a more detailed analysis than we will go into here. Instead of serving as an example of an actual XNOR design, this section should instead help to suggest the methods one could use to generate a CMOS circuit for any arbitrary boolean function.

Input 1	Input 2	Output
0	0	1
0	1	0
1	0	0
1	1	1

XOR

If you've been following along, you may guess that an XOR gate is made by attaching a NOT onto the end of the XNOR; while this will produce *a* correct circuit, it is not the *most* correct (or efficient) circuit. Instead, we could use the same 12 transistors and simply shuffle around the wires. This is left as an exercise for the reader. it uses the logic a.bbar(OR)abar.b

Input 1	Input 2	Output
0	0	0
0	1	1

Input 1	Input 2	Output
1	0	1
1	1	0

Electronics/Integrated Circuits

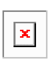
Elements of Digital Circuits

Transistors

Electronics | Foreword | Basic Electronics | Complex Electronics | Electricity | Machines | History of Electronics | Appendix | edit

Transistor

A transistor is a Solid State Device made by joining three positive-type and negative-type semiconductors together. In general, all transistors have three pins: base, collector, and emitter. Transistor is a bi-polar device that is transistor has two junctions namely BE and CE.



Construction

A lightly doped region called base is sandwiched between two regions called the emitter and collector respectively. The collector handles large quantities of current, hence its dopant concentration is the highest. The emitter's dopant concentration is slightly lesser, but its area is larger to provide for more current than the collector. The collector region should be heavily doped because electron-hole pairs recombine in that region, while the emitter is not such a region. We can have two varieties in this kind of transistor.

NPN Transistor

NPN made from joining one positive-type semiconductor in between two negative-type semiconductors. Here a lightly doped p-type semiconductor (semiconductor with more holes than electrons) is sandwiched between two well-doped n-type regions. It is like two pn-junctions facing away. An IEEE symbol for the NPN transistor is shown here. The arrow between the base and emitter is in the same direction as current flowing between the base-emitter junction. Power dissipated in the transistor is

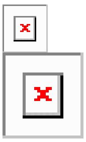
, where

is the voltage between the collector and the emitter and

is the collector current.

PNP Transistor

PNP Transistor made by sandwiching a Nagative-Typed semiconductor in between two Positive-Typed semiconductors.



Transistor Operation

Amplifier

Transistor conducts current when Base Voltage is greater than BE junction's voltage. Current is non zero.

$I_B \neq 0$

$I_E = \alpha\ I_B$

$I_C = \beta\ I_B$

Switch

The characteristic that Transistor conduct or non conduct current make transistor suitable for Electronic Switching. Transistor conducts current when Base Voltage is greater than BE junction's voltage. Current is non zero. This correspond to a Closed Switch. Transistor does not conduct current when Base Voltage is less than BE junction's voltage. Current is zero. This correspond to a Opened Switch.

External links

Wikipedia:Transistor

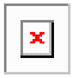
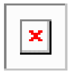
Basic gates

Basic Gates

There are 5 basic gates used in performing logic operations in Digital Electronic namely BUFFER gate, NOT gate, AND gate, OR gate, XOR gate . Each Logic Gate has A Symbol for easy to identify , a Mathematical Expression to identify mathmatic logic operation and a Truth Table to completely describe operation of the Logic Gate

Five Basic Logic Gates

Digital gates	Symbol	Logic Operation	Mathematic Expression
BUFFER		Y = BUFFER A	Y = A
NOT		Y = NOT A	Y =
AND		Y = A AND B	Y = A . B

Digital gates	Symbol	Logic Operation	Mathematic Expression
OR		Y = A OR B	Y = A + B
XOR		Y = A XOR B	Y =

The Truth Table of the five basic logic gates above

A	B	Q = A	Q = NOT A	Q = A AND B	Q = A OR B	Q = A XOR B
0	0	0	1	0	0	0
0	1	0	1	0	1	1
1	0	1	0	0	1	1
1	1	1	0	1	1	0

Complement of Basic Logic gates

Basic Gates	Combination Gates	Symbol	Mathematical Expression
BUFFER			Q = is NOT NOT A Y = A
NOT			Y = is NOT A
NAND			Q = NOT A AND B
NOR			Y = NOT A OR B
XNOR			Q = NOT A XOR B

The Truth table of the combination gates above

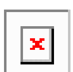
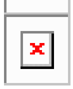
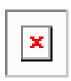
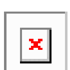
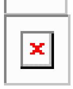
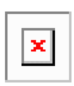
A	B	Q = A	Q = NOT A	Q = A NAND B	Q = A NOR B	Q = A XNOR B
0	0	0	1	1	0	1
0	1	0	1	1	0	0
1	0	1	0	1	0	0
1	1	1	0	0	1	1

Summary

A	B	Q = A	Q = NOT A	Q = A AND B	Q = A OR B	Q = A XOR B	Q = A NAND B	Q = A NOR B	Q = A XNOR B
0	0	0	1	0	0	0	1	1	1
0	1	0	1	0	1	1	1	0	0
1	0	1	0	0	1	1	1	0	0
1	1	1	0	1	1	0	0	0	1

Combination gates

Complement of Basic Logic gates

Basic Gates	Combination Gates	Symbol	Mathematical Expression
BUFFER	 		Y = is NOT NOT A Y = A
NOT	 		Y = is NOT A

Basic Gates	Combination Gates	Symbol	Mathematical Expression
NAND			Y = NOT A AND B
NOR			Y = NOT A OR B
XNOR			Y = NOT A NOR B

Truth table of the combination gates

A	B	Q = A	Q = NOT A	Q = A NAND B	Q = A NOR B	Q = A XOR B
0	0	0	1	1	0	0
0	1	0	1	1	0	1
1	0	1	0	1	0	1
1	1	1	0	0	1	0

XOR

(A AND B) OR (A OR B) = A XOR B

(A.B) + (A+B) = A+B

Flip Flops

Flip Flop

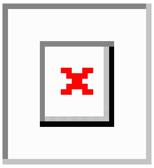
A **flip-flop** is a device very like a latch in that it is a bistable multivibrator, having two states and a feedback path that allows it to store a bit of information. The difference between a latch and a flip-flop is that a latch is asynchronous, and the outputs can change as soon as the inputs do (or at least after a small propagation delay). A flip-flop, on the other hand, is *edge-triggered* and only changes state when a control signal goes from high to low or low to high. This distinction is relatively recent and is not formal, with many authorities still referring to flip-flops as latches and vice versa, but it is a helpful distinction to make for the sake of clarity.

There are several different types of flip-flop each with its own uses and peculiarities. The four main types of flip-flop are : SR, JK, D, and T.

RS Flip Flop

An **SR latch** (Set/Reset) is an asynchronous device: it works independently of control signals and relies only on the state of the S and R inputs. In the image we can see that an SR flip-flop can be created with two NOR gates that have a cross-feedback loop. SR latches can also be made from NAND gates, but the inputs are swapped and negated. In this case, it is sometimes called an **SR latch**.

An SR (Set/Reset) flip-flop is perhaps the simplest flip-flop, and is very similar to the SR latch, other than for the fact that it only transitions on clock edges. While as theoretically valid as any flip-flop, synchronous edge-triggered SR flip-flops are extremely uncommon because they retain the illegal state when both *S* and *R* are asserted. Generally when people refer to SR flip-flops, they mean SR latches.



Circuit symbol for an SR latch.

S	R	Q	Q
0	0	**Latch**	
0	1	0	1
1	0	1	0
1	1	Metastable	

When a high is applied to the *Set* line of an SR latch, the *Q* output goes high (and Q low). The feedback mechanism, however, means that the *Q* output will remain high, even when the *S* input goes low again. This is how the latch serves as a memory device. Conversely, a high input on the *Reset* line will drive the *Q* output low (and *Q* high), effectively resetting the latch's "memory". When both inputs are low, the latch "latches" – it remains in its previously set or reset state.

When both inputs are high at once, however, there is a problem: it is being told to simulataneosuly produce a high *Q* and a low *Q*. This produces a "race condition" within the ciruict - whichever flip flop succeeds in changing first will feedback to the other and assert itself. Ideally, both gates are identical and this is "metastable", and the device will be in an undefined state for an indefinite period. In real life, due to manufacturing methods, one gate will always win, but it's impossible to tell which it will be for a particular device from an assembly line. The state of $S = R = 1$ is therefore "illegal" and should never be entered.

When the device is powered up, a similar condition occurs, because both outputs, Q and Q, are low. Again, the device will quickly exit the metastable state due to differences between the two gates, but it's impossible to predict which of Q and Q will end up high. To avoid spurious actions, you should always set SR flip-flops to a known initial state before using them - you must not assume that they will initialise to a low state.

Characteristic table

S	R	Q_{next}	Comment
0	0	0	Hold state
0	1	0	Reset
1	0	1	Set
1	1	Metastable	

Excitation table

Q	Q_{next}	S	R
0	0	0	X
0	1	1	0
1	0	0	1
1	1	X	0

Gated Flip Flop

Gated SR latch

In some situations it may be desirable to dictate when the latch can and cannot latch. The **gated SR latch** is a simple extension of the SR latch which provides an *Enable* line which must be driven high before data can be latched. Even though a control line is now required, the SR latch is not synchronous, because the inputs can change the output even in the middle of an enable pulse.

When the *Enable* input is low, then the outputs from the AND gates must also be low, thus the *Q* and *Q* outputs remain latched to the previous data. Only when the enable input is high can the state of the latch change, as shown in the truth table. When the enable line is asserted, a gated SR latch is identical in operation to an SR latch.

The *Enable* line is sometimes a clock signal, but is usually a read or write strobe.

Enable	S	R	Q	Q
0	0	0	**Latch**	
0	0	1	**Latch**	
0	1	0	**Latch**	
0	1	1	**Latch**	
1	0	0	**Latch**	
1	0	1	0	1
1	1	0	1	0

Enable	S	R	Q	Q
1	1	1	Metastable	

Gated D latch

The **D latch** (D for "data") or **transparent latch** is a simple extension of the gated SR latch that removes the possibility of invalid input states.

Since the gated SR latch allows us to latch the output without using the *S* or *R* inputs, we can remove one of the inputs by driving both the *Set* and *Reset* inputs with a complementary driver: we remove one input and automatically make it the inverse of the remaining input.

The D latch outputs the *D* input whenever the *Enable* line is high, otherwise the output is whatever the *D* input was when the *Enable* input was last high. This is why it is also known as a transparent latch - when *Enable* is asserted, the latch is said to be "transparent" - it signals propagate directly through it as if it isn't there.

Enable	D	Q	Q
0	0	Latch	
0	1	Latch	
1	0	0	1
1	1	1	0

D latches are often used in I/O ports of integrated circuits and are available as discrete devices, often multiply packaged. An example is the 74HC75, part of the 7400 series of ICs, containing four separate D latches.

Clock - Controlled Flip Flops

D flip-flop

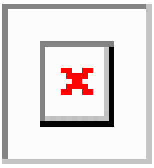
The D flip-flop is the edge-triggered variant of the transparent latch. On the rising (usually, although negative edge triggering is just as possible) edge of the clock, the output is given the value of the D input *at that moment*. The output can only change at the clock edge, and if the input changes at other times, the output will be unaffected.

D flip-flops are by far the most common type of flip-flops and some devices (for example some FPGAs) are made entirely from D flip-flops. They are also commonly used for shift-registers and input synchronisation.

	C	**D**		**Q**	**Comment**
	0	0	Express *D* at *Q*		
	1	1	Express *D* at *Q*		
Otherwise	X	*Q*	Hold state		

JK Flip-flop

The JK flip-flop is a simple enhancement of the SR flip-flop where the state J=K=1 is not forbidden. It works just like a SR FF where J is serving as set input and K serving as reset. The only difference is that for the formerly “forbidden” combination J=K=1 this flip-flop now performs an action: it inverts its state. As the behavior of the JK flip-flop is completely predictable under all conditions, this is the preferred type of flip-flop for most logic circuit designs. But there is still a problem i.e. both the outputs are same when one tests the circuit practically. This is because of the internal toggling on every propagation elapse completion. The main remeady is going for master-slave jk flip-flop,this ff overrides the self(internal) recurring toggling through the pulsed clocking feature incorporated.



Characteristic table

J	K	Q_{next}	Comment
0	0	Q_{prev}	Hold state
0	1	0	Reset
1	0	1	Set
1	1	$\overline{Q_{prev}}$	Toggle

Excitation table

Q	Q_{next}	J	K	Comment
0	0	0	X	Hold state
0	1	1	X	Set
1	0	X	1	Reset
1	1	X	0	Hold state

|}

T flip-flops

A **T flip-flop** is a device which swaps or "toggles" state every time it is triggered if the *T* input is asserted, otherwise it holds the current output. This behavior is described by the characteristic equation:

and can be described either of the following tables:

Characteristic table

T	Q	Q_{next}	Comment
0	0	0	Hold state
0	1	1	
1	0	1	Toggle
1	1	0	

Excitation table

Q	Q_{next}	T
0	0	0
0	1	1
1	0	1
1	1	0

When *T* is held high, the toggle flip-flop divides the clock frequency by two; that is, if clock frequency is 4 MHz, the output frequency obtained from the flip-flop will be 2 MHz. This 'divide-by' feature has application in various types of digital counters. A *T* flip-flop can also be built using a JK flip-flop (J & K pins are connected together and act as T) or D flip-flop (*T* input and Q_{prev} are connected to the *D* input through an XOR gate).

Counters

Overview

A counter is a device that generates some patterned binary value depending on a clock or some other pulsed input. There are three simple types of counters ripple and synchronous.[[

Types of Counters

Ring Counters

If the output of a shift register is fed back to the input. a ring counter results. The data pattern contained within the shift register will recirculate as long as clock pulses are applied. For example, the data pattern will repeat every four clock pulses in the figure below. However, we must load a data pattern. All 0's or all 1's doesn't count. Is a continuous logic level from such a condition useful?

[3]

We make provisions for loading data into the parallel-in/ serial-out shift register configured as a ring counter below. Any random pattern may be loaded. The most generally useful pattern is a single 1.

[4]

Loading binary 1000 into the ring counter, above, prior to shifting yields a viewable pattern. The data pattern for a single stage repeats every four clock pulses in our 4-stage example. The waveforms for all four stages look the same, except for the one clock time delay from one stage to the next. See figure below.

[5]

The circuit above is a divide by 4 counter. Comparing the clock input to any one of the outputs, shows a frequency ratio of 4:1. How may stages would we need for a divide by 10 ring counter? Ten stages would recirculate the 1 every 10 clock pulses.

[6]

An alternate method of initializing the ring counter to 1000 is shown above. The shift waveforms are identical to those above, repeating every fourth clock pulse. The requirement for initialization is a disadvantage of the ring counter over a conventional counter. At a minimum, it must be initialized at power-up since there is no way to predict what state flip-flops will power up in. In theory, initialization should never be required again. In actual practice, the flip-flops could eventually be corrupted by noise, destroying the data pattern. A "self correcting" counter, like a conventional synchronous binary counter would be more reliable.

[7]

The above binary synchronous counter needs only two stages, but requires decoder gates. The ring counter had more stages, but was self decoding, saving the decode gates above. Another disadvantage of the ring counter is that it is not "self starting". If we need the decoded outputs, the ring counter looks attractive, in particular, if most of the logic is in a single shift register package. If not, the conventional binary counter is less complex without the decoder.

[8]

The waveforms decoded from the synchronous binary counter are identical to the previous ring counter waveforms. The counter sequence is (QA QB) = (00 01 10 11).

Ripple Counters

Ripple counters are the simplest type of counters. They are nothing more than toggle flip flops connected in a chain to divide each others output frequency by two. The result is a binary count. They are called ripple counters because the new count ripples through them. The major disadvantage of ripple counters is that because of new count "rippling" through the flip flops all the bits of the count arrive at different times.

Synchronous Counters

Synchronous counters are simple state machines made out of flip flops and logic gates. They have two parts, a register made out of flip flops and a decoder made out of logic gates. A register is a simple group of flip flops that are all clocked at the same time. In this way they can hold the counters output value until the next clock cycle. The decoder, decodes the current count and generates the correct value for the next count to the flop flops. For example in a simple up counter the decoder would always output the current count plus one. The major advantage of Synchronous Counters is that all the bits of their output change at the same time.

Adders

Intro

When adding one number A with another number B the operation will produce a Sum S and a Carry C.The Operation of an adder is Shown below.

Digital Adder

Half adder

If there are two binary number A and B . The operation of adding two numbers can be shown below

A + B = S C

0 + 0 = Sum 0 Carry 0

0 + 1 = Sum 1 Carry 0

1 + 0 = Sum 1 Carry 0

1 + 1 = Sum 0 Carry 1

The operation of Half Adder can be summarized in the Truth Table below

0	0	0	0
0	1	0	1
1	0	0	1
1	1	1	0

From above, In term of logic gate XOR will produce a sum of two input . logic gate AND produce carry

Half Adder can constructed from AND gate and XOR gate as shown below

```
                _____________
     A ------|               |
             |    Half       |-----

             |    Adder      |
             |               |-----

     B ------|_____________|
```

Full adder

A **full adder** is a logical circuit that performs an addition operation on three one-bit binary numbers. The full adder produces a sum of the two inputs and carry value. It can be combined with other full adders (see below) or work on its own.

Input	Output			
0	0	0	0	0
0	1	0	0	1
1	0	0	0	1
1	1	0	1	0
0	0	1	0	1
0	1	1	1	0
1	0	1	1	0

Input	Output				
1	1		1	1	1

Note that the final OR gate before the carry-out output may be replaced by an XOR gate without altering the resulting logic. This is because the only difference between OR and XOR gates occurs when both inputs are 1; for the adder shown here, this is never possible. Using only two types of gates is convenient if one desires to implement the adder directly using common IC chips.

A full adder can be constructed from two half adders by connecting *A* and *B* to the input of one half adder, connecting the sum from that to an input to the second adder, connecting C_i to the other input and OR the two carry outputs. Equivalently, *S* could be made the three-bit XOR of *A*, *B*, and C_i, and C_o could be made the three-bit majority function of *A*, *B*, and C_i.

Multiple-bit adders

Ripple carry adder

It is possible to create a logical circuit using multiple full adders to add *N*-bit numbers. Each full adder inputs a C_{in}, which is the C_{out} of the previous adder. This kind of adder is a *ripple carry adder*, since each carry bit "ripples" to the next full adder. Note that the first (and only the first) full adder may be replaced by a half adder.

The layout of ripple carry adder is simple, which allows for fast design time; however, the ripple carry adder is relatively slow, since each full adder must wait for the carry bit to be calculated from the previous full adder. The gate delay can easily be calculated by inspection of the full adder circuit. Each full adder requires three levels of logic. In a 32-bit [ripple carry] adder, there 32 full adders,so the critical path (worst case) delay is

gate delays.

Carry look-ahead adders

To reduce the computation time, engineers devised faster ways to add two binary numbers by using carry lookahead adders. They work by creating two signals (*P* and *G*) for each bit position, based on whether a carry is propagated through from a less significant bit position (at least one input is a '1'), a carry is generated in that bit position (both inputs are '1'), or if a carry is killed in that bit position (both inputs are '0'). In most cases, *P* is simply the sum output of a half-adder and *G* is the carry output of the same adder. After *P* and *G* are generated the carries for every bit position are created. Some advanced carry look ahead architectures are the Manchester carry chain, Brent-Kung adder, and the Kogge-Stone adder.

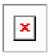
4-bit adder with Carry Look Ahead

Some other multi-bit adder architectures break the adder into blocks. It is possible to vary the length of these blocks based on the propagation delay of the circuits to optimize computation time. These block based adders include the carry bypass adder which will determine *P* and *G* values for each block rather than each bit, and the carry select adder which pre-generates sum and carry values for either possible carry input to the block.

Other adder designs include the conditional sum adder, carry skip adder, and carry complete adder.

Lookahead Carry Unit

By combining multiple carry look-ahead adders even larger adders can be created. This can be used at multiple levels to make even larger adders. For example, the following adder is a 64-bit adder that uses four 16-bit CLAs with two levels of LCUs.



A 64-bit adder

Reference

1. Digital Adder on Wikipedia

Decoders and Encoders

Encoders

Encoders are devices that act on data to transform it in such a way that the data acquires some new characteristics. These characteristics can vary from reduction in length to inclusion of error correction properties to use of security measures. At the most basic level, encoders can be used to reduce the size of data. Consider the following block diagram :

```
          ____
A ---|        |
B ---|        |-- X
C ---|        |-- Y
     |____|
```

If out of ABCD only one is high at any given time, then we can only have the following possibilities for input : 000, 001, 010, 100. Thus we can make the internal circuit of the encoder in such a way that when it sees 000 it outputs 00, when it sees 001 it outputs 01, when it sees 010 it gives 10 and when it sees 100 it outputs 11

```
    __________
---| 000 | 00 |
---|-----|----|
---| 001 | 01 |
---|-----|----|
---| 010 | 10 |
---|-----|----|
---| 100 | 11 |
---|_____|____|
```

Thus we have effectively reduced the size of the data, by exploiting the fact that all possible combinations of input will never be provided at the input terminals.

The internal circuit of the encoder can be easily derived by using truth tables

```
    _____________________
---| A | B | C ||| X | Y |
---| 0 | 0 | 0 ||| 0 | 0 |
---| 0 | 0 | 1 ||| 0 | 1 |
---| 0 | 1 | 0 ||| 1 | 0 |
---| 1 | 0 | 0 ||| 1 | 1 |
---|___|___|___|||___|___|
```

Clearly X = A + B and Y = A + C

So the circuit diagram can be :

```
A ----------[ OR ]----------X
    |   B---[ OR ]
    |
    |-------[ OR ]----------Y
        C---[ OR ]
```

This scheme can be extended for n inputs.

This was a very basic encoder, it could act only on data when a single line was high. It is possible that multiple lines may be high, in that case one may use priority encoders which assign output based on priority, that is if two lines are high, for example A and C in the previous example, then a priority encoder will, based on a prior decision by the designer, decide to assign output to either C or A thereby assigning it a higher priority.

In some cases we don't want priority encoding, rather when faced with multiple signals, we wish to create a new code for that particular combination as well, and still obtain some reduction in size.

At other times we may wish to modify the incoming code in a manner that allows the receiver to detect any errors that may have crept in during transmission. These topics will be elaborated upon in appropriate topics.

Multiplexers

Overview

A multiplexer is a device that brings the concept of a rotary switch in analog electronics to the digital side. It is a device which, based on some input, will change the connection of its other inputs to its outputs. Conceptually a digital multiplexers functionality is the same as an analog one, only it handles everything digitally. Because of the mathematical concept of combinatorix they can be used to replace chain logic circuits. However, this is not done frequently because multiplexer based logic has a comparably high propagation delay.

Configuration

File:Decoder Example.svg

The circuit above has 2 Control Lines A1Ao which can be used as 2 Selectors . Depend on the value of the Selectors only one of the Output Lines can be high . The circuit above has the capability to select the output line

The operation of the circuit above can be summarized in the Truth Table below

A_1A_0	$D_3D_2D_12_0$
00	0001
01	0010
10	0100
11	1000

In general

2 Selectors can select $2^2 = 4$ output lines

3 Selectors can select $2^3 = 8$ output lines

n Selectors can select 2^n output lines

Computer Architecture

RAM and ROM

RAM: Random Access Memory ROM: Read Only Memory

Basics

Capacitors as memory

- Capacitors can be charged, and when they are charged they can be discharged.
- When charged they act like a source of voltage but only for a limited time unless they are "refreshed".
- If charged they can be "refreshed" by charging them again and again to keep their voltage above a specified minimum. This procedure can be quite automatic at regular intervals and applies ONLY to capacitors that already have a voltage that is above that set minimum.
- "Writing" into a capacitor-memory means either charging that capacitor or discharging it as required. We say that a memory is "a zero" if its voltage is below a specified value, and it is "a one" if above. Putting a 1 into the memory means charging the capacitor, while putting a 0 into the memory means discharging the capacitor.
- "Reading" a capacitor-memory is equivalent to putting a voltmeter across its terminals to see whether its voltage is or is not above a given minimum.

NOTE: Modern memories use transistors, gates, diodes, etc.

Examples

Reference 1: Programmer's Reference Guide for the Commodore 64 Personal Computer, published in 1988 by Commodore Business Machines, Inc.

- part of the microprocessor 6510's characteristics:

- For a 0 the minimum is minus 0.3 Volt, and the maximum is plus 0.3 Volt.
- For a 1 the minimum is plus 2.0 Volt, and the maximum is 1 Volt above the supply voltage which usually is about 5 Volt, but whose absolute maximum is 7.0 Volt. Note that static electricity (by friction on the carpet for example) can cause a lot of damage and must be guarded against.

Reference 2: The Semiconductor Memory Data Book for Design Engineers, published in 1975 by Texas Instruments Inc.

Bits

- Think of "one bit" as one memory unit, such as one capacitor-memory. It can have a 0 or a 1 "in it", as required; a "High" (H) usually is a 1, and a "Low" (L) usually is a 0. Bit is a shortened version of binary digit.

Bytes

- A byte is a group of bits. One bit can only represent "a count" of zero or one, two bits grouped together into a byte can represent a count of zero to 3, 3 bits into a byte can count up to 7 and n bits in a byte can count up to 2^n minus 1. A byte with 8 bits in it can count from 0 to 255. "Words" are bytes; they each have a stated number of bits in them.
- Bytes can also be combined; 2 bytes, each with 8 bits in it, can count up to 256 times 256 minus 1, that is 0 to 65535.

Words

- Words are a concept that dates back to early computer architectures, where a single "unit" of memory was different from 8 bits. Common early word sizes were often 10 bits, but sometimes six or 20 bits.
- Generally a word was defined as the size of the memory bus for internal storage (i.e. RAM or ROM), as well as the minimum independently addressable unit of memory.
- Most modern CPU architectures use independently addressable byte architecture, but some modern CPUs (like the Pentium and other x86 CPUs) perform memory and instruction tasks more efficiently if the memory is "aligned" on word boundaries.
- Terms like **word** and **longword** date back to 16-bit and 32-bit CPU architectures respectively, and to give a common framework for backward compatible software tools. More recently, the term **quadword** is used to denote a 64-bit piece of memory, although the term **octaword** is sometimes used (because it is 8-bytes being accessed at once).
- Endian architecture defines how the memory is encoded within the RAM of the computer and its relationship with the byte addresses. Generally this is not an issue for most software except when you write data files meant for consumption on multiple platforms that have multi-byte components.

Address Bus connection

Just as the mail delivery person needs to have an address on each item to be delivered/collected, so also access to a particular byte of memory is "delivered" to a particular address, or "collected" from a particular address.

- For example a memory can have 16 address connections, labelled 0 to 15. That means that data can be fed into, or taken out of, a specific memory cell, whose address is between 0 and (2^{16} minus one), which is between 0 and 65535.

Data Bus connection

After the specific address has been fed into the memory, a specific given number is fed ("written") into the data bus connection, or the content of that address is "read".

- For example a memory can have 8 data connections, labelled 0 to 7. That means that the number fed into the selected byte must be between 0 and (2^8 minus one), which is between 0 and 255.

Read/Write connection

There is also an input terminal connection that indicates the operation required. A 0 into that connection may indicate that the next operation will be a "write", while a 1 may indicate that it will be a "read".

Clock connection

A memory may require one or more clock signals, possibly "phase 1" and "phase 2", etc., which are inputs into the memory from oscillators, meaning they alternate very fast between 0 and 1 continuously. While the clock is, maybe, 0 various changes can be made, such as an address change and/or a change of data, but the actual reading or writing takes place only while the clock is, maybe, 1. Some memories include clock oscillators, possibly requiring external crystals.

RAM (Random Access Memory)

A RAM is a "Random Access Memory" - Sizes and their architecture vary considerably, users can put into any of their addressed bytes any number up to a given maximum, and that number can be replaced by another number as required, when required. Some memories supply the complements of what was put into them.

- For example a memory with 1024 bits can require only a 0 or 1 to be put into any of the 1024 cells, while another memory can require 4 bits (0 to 15) per word, but only 16 words can be retained at a time, etc.

Dynamic Read/Write Memories

Requires frequent refreshing.

Static Read/Write Memories

Retains the data even if control signals are absent, however such memories may use dynamic addressing

ROM (Read Only Memory)

A ROM is a "Read Only Memory". It is factory-produced, and usually its contents are fixed. A ROM can be read, but it usually cannot be written to. Usually a ROM contains very important fixed information required for the proper operation of the equipment.

Mask-Programmed Read-Only Memories

Uses a mask during manufacture, contents cannot be altered.

Programmable Read-Only Memories

Permits a change of each cell after manufacture, but once only.

Reprogrammable Read-Only Memories

Permits changes to each cell after manufacture, more than once.

Registers

Registers

Registers can move two types of digital information: parallel and serial. Registers also have two basic ways of moving it: FIFO and LIFO. The simplest register is a FIFO, which is only one level deep and one bit wide. It is basically a single D Type Flip/Flop.

FIFO

A FIFO (First In First Out) is a digital device that moves data in the same way a queue would. The first chunk of information in is moved over as more is loaded in behind it. This continues until it is pushed out the end. Like a grocery line.

LIFO

A LIFO (Last In First Out) is a like a FIFO only the data comes out in the reverse order it came in. Data is processed like a stack data structure. Imagine putting items onto a stack, the first item taken off would be at the top of the stack. Thus, the last item in (item at the top of the stack), would be the first item out

Parallel

Parallel Registers take in mulitple bits at a time.

Shift Registers

Shift Registers are the simplest serial interfaces. They take serial data in one bit at a time and convert it to parallel form or the other way around. The first way is Serial In Parallel Out and the latter is Parallel In Serial Out. Shift Registers are used to make larger state machines like counters and UARTs.

Serial In Parallel Out

Tons of information about Serial in Parallel out circuits and how they are constructed

Parallel In Serial Out

ALU

Arithmetic and Logic Unit

Introduction

The Arithmetic and Logic Unit are not a single entity, but are actually composed of two separate units whose operation is highly dependent on the Select Input(S).

This input, is a one-bit input, that will decide whether to route the binary variables to the Arithmetic, or to the Logic Circuit.

Arithmetic Unit

Handles basic operations such as Addition and Subtraction. The Multiplication and Division operations are dependent on the basic operations, and Bit-Shifting. The Multiply and Divide operations, can also be implemented using Hardwired / Microprogrammed Control.

Logic Unit

The Logic unit, is a Hardware Unit, implemented for performing basic operations such as AND, OR, NAND, and NOT. A particular logical operation is selected using a 4:1 Demultiplexer.

The results of all the operations are routed into a data bus for memory addressing.

further reading

- Microprocessor Design/ALU

Control Unit

The Control Unit provides the Micro-Instructions that are necessary for the execution of a program. The micro instruction that should be executed next is decided based on the Current instruction fetched from memory and the bit values off the Various CPU status registers such as Negative, Zero etc.

Of the two CPU architectures in use the RISC (Reduced Instruction Set Computing) and the CISC (Complex Instruction Set Computing) have different philosophies in this regard where the RISC believes in having a larger number of more simple Micro-instructions and the CISC believes in a smaller number of more complex instructions.

further reading

Wikipedia has related information at ***control unit***

- Digital Circuits/Finite State Machines describes low-level detail of state machines in general, which includes control units.
- Microprocessor Design describes some very complicated control units, and how to design your own.

I/O

Input/Output

Input

For example: a computer disk can have a lot of information on it, and the user selects a particular disk for the task in hand. Then the user activates an **input** procedure to have the computer move a copy of the given required information from the disk, where the original remains, into a part of the computer's memory for further use. The original on the disk can, if desired, be deleted.

Output

For example: Some work has been done using a computer, and now the result is to be moved from the computer onto a disk, which is one of many possible **output** devices. Usually the computer's screen, which is also an **output** device, shows exactly what is being done by the user so as to ensure the information concerned ends up at the correct place, **outside** of the computer. Often a printer is used, which is another **output** device.

RTN

Electronics | Foreword | Basic Electronics | Complex Electronics | Electricity | Machines | History of Electronics | Appendix | editElectronics:Computer Architecture

RTN (Register Transfer Notation)

Register Transfer Notation is a way of using special math notation to analize different types of computer architectures. RTN easily shows the number of transfers and clocks required for a given architecture to do a specific process.