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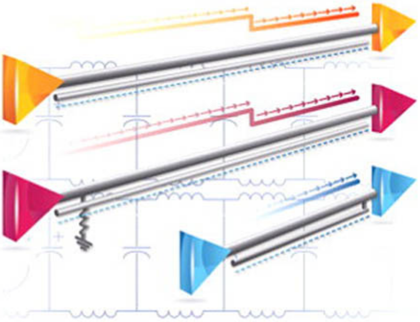
PCB Currents

How they Flow, How they React



Douglas Brooks

Prentice Hall Modern Semiconductor Design Series
Prentice Hall Signal Integrity Library

PCB Currents

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How They Flow, How They React

Douglas Brooks

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*T*here are a great many PCB designers in the world who do not have a technical degree. There are many others who have degrees, but either did not get all the information they needed, or forgot some of what they learned earlier. These designers struggle each day to keep up in an industry that is advancing very rapidly. This book is dedicated to them with the sincere hope that it will help them on their journey.

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PREFACE

I have spent most of my working career in various positions in the electronics industry. The last twenty of those years have been associated with printed circuit board design. I have enjoyed this last association very much, and have met many people in the industry through the preparation of articles and presentation of seminars. I have been fortunate enough to have been invited to give seminars in such wonderful places as Moscow, Beijing and Shanghai, Taiwan, Japan, and Australia (as well as all over the United States.). The industry has been good to me!

Good PCB designers are artists with excellent pattern recognition skills. I still marvel, after all these years, at how a designer looks at a computer screen, grabs the beginnings of a trace, and then routs that trace, panning across the equivalent of many screens, to the other end of the net, all the time knowing exactly where he or she is going. When finished, the board looks beautiful—almost a work of art. This is sometimes disparagingly referred to as "connecting the dots." But it is so much more than that.

But in the last twenty years or so PCB designers have had to deal with another set of requirements. These have arisen because the board has started to look like a component, with resistance, capacitance, and inductance, rather than just an interconnection platform. This, in turn, requires PCB designers to know something about electronic components and current flow. Not a lot. They don't have to be engineers. But they DO have to know a lot of things that engineers (are supposed to) know.

The thing that has struck me during my travels is that even though PCB designers deal with very complex circuits and requirements, very few of them have any formal training in electronics. So even though things like the impedance matching of traces can be important, many of them don't know what impedance means! They have to worry about crosstalk and EMI, but don't know what these are or why they happen. And ground bounce? Well, you see what I mean.

With Pete Waddell's (UP Media Group) backing, I developed a seminar on basic electronics back in the early 90s that I have given at several PCB Design trade shows. Prentice Hall published an expanded version of that effort in 2003: *Signal Integrity Issues and Printed Circuit Board Design*. This was, I hope, a helpful contribution to many designers. And while I was (and am) satisfied with that effort, I have always felt it was not as well focused as it could have been.

That feeling has led to this current (no pun intended) version!

Focus

The focus of the book is on current, what it is, how it flows, and how it reacts. Each chapter discusses a specific characteristic of current under specific conditions.

Organization

The book is organized into four parts:

Part I	Nature of current
Part II	Current flow in basic circuits
Part III	Sources that supply and drive current
Part IV	The special problems related to current on circuit boards

The fundamental particle in electronics is the electron. It is no accident that the field is called *electron-ics*. All elements in the universe are made up of protons, neutrons, and electrons. Protons are positively charged and electrons are negatively charged. Fundamental particles (indeed the entire universe) are "charge neutral." By that I mean there is pretty much an equal number of protons and electrons everywhere.

Nothing much happens if electrons don't move. We can have static charge fields caused by localized differences in charge, and these charge fields can matter. But still, the game doesn't start to get really interesting until electrons start to move within these fields. When electrons move, we have (by definition) a current. And that is what electronics is all about.

Part I covers the fundamental nature of current. Chapter 1 introduces the basic definition of current (the flow of electrons). Specifically, one amp of current is the flow of 6.25×10^{18} electrons across a surface in one second of time. Chapter 2 introduces several current concepts, from frequency and waveforms to propagation speeds to measures of current and how to take those measurements. Chapter 3 introduces five fundamental laws of current:

1. Current flows in a loop
2. Current is constant everywhere in the loop
3. Kirchhoff's First Law (current into a node equals current out of the node)
4. Kirchhoff's Second Law (voltage around a loop sums to zero)
5. Ohm's Law (relationship between current, voltage, and impedance)

It is important to recognize that this much is all that is required (conceptually) to solve even the most complex resistive circuit. (The introduction of AC and reactance adds some complication, but conceptually, not much!) Simply break a circuit up into its n individual loops, set up a set of n simultaneous equations using Kirchhoff's and Ohm's Laws, and solve them using matrix algebra. (Easy to say!) Conceptually, this is straightforward. A typical course in EE 101 covers this much material. The rest of the EE curriculum covers the techniques for how you actually do solve those circuit problems and calculations!

Part II covers various circuit concepts, starting with resistive circuits, then reactive circuits (capacitors and inductors), then impedance (i.e. what happens when you combine all these components.) Individual chapters cover time constants, transformers, differential circuits, and current flow through semiconductors.

It is important to note that there are really only three passive components we deal with, resistance, capacitance, and inductance. In a very real sense, these components occupy special places on a spectrum. Capacitance is at one end (impedance goes to zero when frequency goes to infinity, and the voltage phase shift is -90 degrees.) Inductance is at the other end (impedance goes to infinity when frequency goes to infinity, and the phase shift is +90 degrees.) And resistance occupies a special place right in between (impedance is independent of frequency and the phase shift is zero.) These three facts are *universally* true; they never change.

Part III is a short section that covers voltage and current sources. If we want to get a current (i.e., a flow of electrons) where do the electrons come from and how to we force them to move.

Part IV deals with the special problems that are introduced by printed circuit boards. Most (but admittedly not all) electronic systems have circuit boards in them. If frequencies are high enough (or, as I point out the real issue is if rise times are fast enough), or if current magnitudes are high enough, circuit boards present special problems that need to be addressed.

Individual chapters cover such things as current and trace temperatures, transmission lines and reflections, coupled currents (EMI and crosstalk), power distribution, skin effect and dielectric losses, and vias.

Finally, the last chapter deals with signal integrity issues caused by current flow. In my career I have seen the industry progress through four stages with respect to signal integrity issues on circuit boards. The first stage is trivial; there were no problems. The second stage involves (mostly) problems caused by inductance on the board itself. The third stage involves the apparent change in resistance caused by very high frequencies (i.e., skin effect or dielectric losses.) These are not REAL changes in resistance, but they *act* as though they are. Finally, the fourth stage occurs when frequency harmonics are so high, and wavelengths so short, that it is extremely difficult to implement solutions in such short physical distances. This chapter deals with various design rules for dealing with these problems.

The book also has three appendices. Appendix A covers James Clerk Maxwell, his equations, and his concept called *displacement current*. Appendix B introduces and gives a brief explanation of eye diagrams. Appendix C is more of a personal note. During my career I have heard people predict the death of PCBs numerous times. Each time they have been wrong—and always for the same reason. Appendix C gives my view as to why.

Since Parts III and IV deal primarily with circuit boards, this book would seem to be aimed narrowly at this audience. But when you recognize that almost all electronics these days are interconnected on circuit boards, I don't believe it is as narrow as perhaps perceived. We have circuit boards in TVs and computers, for sure. But we also have them in our security alarms, irrigation controls, light dimmers, washers and dryers, refrigerators, ovens, timers, clocks, and untold other products. And who can count the number of circuit boards that exist in a modern automobile?

Target Audience

This book is targeted at PCB designers and those who would like to be PCB designers. The book does not have the depth required for a rigorous course in a EE degree program. It might be useful, however, for students in other degree programs where a brief introduction to electronics is important. Such programs might be found at the university level, trade school level, at community colleges, or special programs targeted at existing designers looking to increase their general knowledge. It would also be useful for engineers who, for whatever reasons, have become "rusty" with respect to what they originally learned (or perhaps didn't learn!) their first time through school.

The book is intentionally written in plain English with a minimum of mathematics. The nature of electronics is the flow of electrons, which is a time-variant phenomenon. By definition, this is a situation that involves calculus. I can vouch for the fact that EEs get more calculus in their education than they ever thought existed! Some use of formulas is simply unavoidable. Ohm's Law is a formula! But I have tried to use as few formulas as possible and have used only the most important ones (I believe) in our field.

ACKNOWLEDGMENTS

I have been in the PCB Design industry for a little more than twenty years. During that time, there have been a great many people who have helped guide my growth. While it has been a business, I have also looked for ways to contribute to the industry and to the people who make it up. Pete Waddell, in particular, was one of the first who encouraged me to write articles and then, later, to give seminars, and offered me a vehicle to do that. This book is the end result of what started from that early encouragement.

Along the way there have been many people I have associated with who have helped and encouraged me. And many I have learned from. These are all too many to count and to mention. But they include all those who have also given seminars on signal integrity issues.

Dave Graves has been my partner for the full twenty years. I am completely indebted to him for his support and dedication through the years. I have routinely shown him drafts of articles and presentations, and I can't tell you how many times I've gone back to the drawing board when his response was "I don't get this! What are you trying to say?" Everything is better because of his reviews and support. Now that I am retired, and we have gone our separate ways, I miss that association.

I would also like to acknowledge three vendors who have been especially generous with their support for my article and seminar activities through the years. Mentor Graphics, HyperLynx (now a part of Mentor), and Polar Instruments have offered licensing and technical support whenever asked. And I appreciate the fact that they have offered that support without ever trying to exert any type of control over any of the ways that support was being used.

I've enjoyed preparing this book and have mixed emotions now that it is finished. But there are a couple of people who are *really* happy this project is finally finished, particularly my (nontechnical) wife. She thinks that *now* (maybe) I may actually be retired!

Finally, I am grateful for the support and encouragement I received from Bernard Goodwin at Prentice Hall. This is the second time he has helped guide me through the publishing process. I hope he, and you, the reader, determine that it has all been worthwhile.

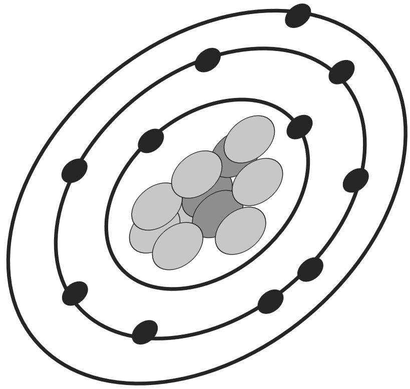
ABOUT THE AUTHOR

Douglas Brooks has a B.S./E.E. and M.S./E.E. from Stanford and a Ph.D. from the University of Washington. He has had forty years of experience in the electronics industry, ranging from circuit design engineer on the space program to president of his own manufacturing company. For the past twenty years, he has been president of UltraCAD Design, Inc., a premier PCB Design Service Bureau in the Pacific Northwest.

Brooks has published hundreds of articles during his career. In the last twenty years, these articles have appeared in *PCB Design Magazine*, on Iconnect007's websites, on Mentor Graphics' web pages, and on UltraCAD's web pages. In 2003, he published the book *Signal Integrity Issues and Printed Circuit Board Design* (Prentice Hall).

Brooks served on the faculty of San Diego State University for three years and was a visiting associate professor at the University of Washington for one year. He has given numerous seminars on Signal Integrity Issues in PCB Design over the past fifteen years all over the United States and in Moscow, Beijing and Shanghai, Taiwan, Japan, and Australia.

Brooks finally retired in 2012.



1 Electrons and Charges

1.1 The Flow of Electrons

Current is the flow of electrons. This is the most important definition in this book! If there is a current, electrons are moving, and if there is no current, electrons are not moving. It's that simple. It is no accident that the world of voltages and currents is called *electronics*.

When we measure current, we are determining how many electrons are moving. The definition of 1 amp of current is 1 coulomb of charge (6.25×10^{18} electrons)

Technical Note

Some would argue that this statement is not true, stating that current is a stream of photons or a wave phenomenon. While these statements are not totally wrong, the core definition is the correct one. Nobel Prize–winning physicist Richard Feynman said the following:[1]

> In an atom with three protons in the nucleus exchanging photons with three electrons—a condition called a lithium atom—the third electron is

(*Continues*)

1. Richard Feynman, *QED: The Strange Theory of Light and Matter* (Princeton, NJ: Princeton University Press, 1985), 113.

Technical Note (*Continued*)

further away from the nucleus than the other two (which have used up the available space) and exchanges fewer photons. This causes the electron to easily break away from its own nucleus under the influence of photons from other atoms. A large number of such atoms close together easily lose their individual third electrons to form a sea of electrons swimming around from atom to atom. This sea of electrons reacts to any small electrical force (photons), generating a current of electrons—I am describing lithium metal conducting electricity. Hydrogen and helium atoms do not lose their electrons to other atoms. They are "insulators."

passing by a point (or across a surface) in 1 second. So one way to measure current is to actually count the number of electrons passing by a point in one unit of time. Of course, electrons are small and hard to see, so it is not practical to count each individual one. But if we could, that would be one way to measure current. Actual current measurement methods are outlined in Chapter 2.

Why is it important that electrons can move? The answer is because we can do useful things with that information if we have it under control. Suppose we move electrons back and forth along a conductor at a frequency that is the same as the pitch (frequency) of some music we are listening to. Suppose we move more electrons when the music is louder and fewer electrons when the music is quieter. That is, we let the magnitude of the electron flow (the current) be proportional to the volume of the music. The frequency and magnitude of the current flow therefore becomes an analog of the music. There are several ways we can transmit music across a room, but current flow is a very convenient way to transmit (an analog of) music across long distances.

Or suppose we can place a large number of electrons at one point in a circuit at one point of time and a smaller number of electrons at another point in time. These two different levels of electrons can represent one bit of information.[2] If we have thousands or millions of such points available to us (as in a microprocessor), we can assemble these bits of information into meaningful communication or information processing systems.

2. One bit of information is the amount of information that is contained in a "yes" or "no" answer. It forms the basis of binary or digital logic.

1.2 Atomic Structure

An *electron* is one particle of atomic structure. A simplified model of an atom is shown in Figure 1-1. The model represents an atom consisting of three basic particles: protons, neutrons, and electrons. The protons and neutrons are coupled tightly together at the center, or nucleus, of the atom, and the electrons rotate in concentric circles around the nucleus.[3] This model is called a *planetary* model because the electrons resemble planets orbiting around the sun. This is typical of what the world's understanding of atomic structure was about 100 years ago. We now know that an atom is much more complex than this. Still, this simplified model is very useful for our understanding of the basic nature of current flow.

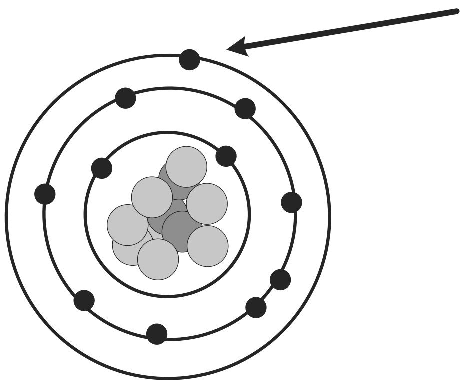


Figure 1-1 Planetary model of an atom.

Protons and neutrons are very similar to each other, with one exception. Each proton has one unit of positive charge, whereas neutrons have no charge. Electrons each have one unit of negative charge. All stable elements in nature must be charge neutral, so in any element (atom) there must be an equal number of protons and electrons.

The number of protons (and therefore the number of electrons) in an atom is called the *atomic number*. The atomic number is what distinguishes one element from another in nature. For example, hydrogen has an atomic number of 1. An atom of hydrogen has a single proton and a single electron. Helium has an atomic

3. In reality, they do not occupy circular, concentric orbits, but different energy "shells."

number of 2. A single helium atom has 2 protons and 2 electrons. Copper has an atomic number of 29, so it contains 29 protons and 29 electrons.

The atomic weight (sometimes called atomic mass) of an atom is approximated by the sum of the number of protons and the number of neutrons in the nucleus of the atom. Hydrogen has an atomic number of 1 and an atomic weight of 1 because it has no neutrons. The atomic weight of helium is 4 (recall that the atomic number is 2). An atom of helium has 2 protons and 2 neutrons. The atomic weight of copper is 64; it has 29 protons and 35 neutrons.[4]

The *Periodic Table* (of the Elements) is the primary way we display information about atomic structure and the identification of the various elements. Anyone who has taken chemistry in school has seen a periodic table (at least I hope so). A search for "periodic table" on the Web will turn up *millions* of hits. A major advantage of Web-based tables (over their text-based counterparts) is that Web-based tables are frequently animated, greatly helping our understanding of the information they convey.

What is most important for us to understand is how the electrons of an atom are organized around the nucleus. We think of electrons as orbiting around the nucleus in concentric spheres (sometimes called *bands* or *shells*). But there is a very definite order in how this happens. Each sphere has a maximum number of electrons it can hold. And the spheres must be filled in order. That is, each inner sphere must be filled to capacity before electrons can begin to fill the next sphere. The first sphere can contain two electrons. A hydrogen atom has 1 electron in this sphere. A helium atom has 2 electrons in this sphere, filling it. Lithium (with an atomic number of 3) has 2 electrons filling the inner sphere and 1 electron in the next sphere.

The outermost sphere (or band) of an element is called the *valence band*. It is the nature of this valence band that is important to us and to current flow. Electrons, being negatively charged, are naturally attracted to protons with their positive charge. Their energy level in their various bands is what keeps them from collapsing into the nucleus. This is very analogous to the gravitational attraction of planets to the sun. Planets would collapse into the sun if it weren't for their rotational energy in circulating around the sun. If the valence band of an element has a single electron in it, that electron, being relatively "farther away" from the nucleus, is, relatively speaking, more loosely attached to the atom. We sometimes (not altogether appropriately) refer to it as a "free" electron. On the other hand, when a valence band is completely filled with electrons, those electrons are relatively tightly held by the nucleus.

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4. The atomic number of an atom defines it as an element. Different isotopes of an element have different atomic weights.

Let's go back to the idea that current flow is the flow of electrons. Elements that hold the electrons loosely in the valence band—those with only a single electron in the valence band, for example—give up those electrons fairly easily. These elements, therefore, act like *conductors*. Electrons can move relatively freely through such conductors without much external energy being applied. On the other hand, elements that hold their electrons very tightly—those whose valence bands are more fully occupied—do not allow the free flow of electrons. Therefore, they are the opposite of conductors; they are insulators.

We intuitively know that copper, silver, and gold are excellent conductors of current. These elements have two characteristics that make them good conductors: They are solid at room temperature and they each have a single electron in their valence band.

When the atoms of a conductor element are formed into a conducting wire or trace, they cluster together in a crystalline structure. Each element has its own special way of combining with other similar elements, but with gold, silver, and copper, the structure is such that it is not immediately clear which atomic nucleus "owns" which valence band electron. The nuclei can share, or trade, these valence electrons with very little effort. So if there is a force that tends to pull or push electrons in a particular direction, the electrons can shift from one nucleus to an adjacent one with relative ease. This process is illustrated in Figure 1-2. Some force is moving the electrons from left to right. Some electrons move from one nucleus to the next, while some *jump* over several nuclei before settling into another valence band. Studies have suggested that the typical transition of electrons among atoms in a copper structure when current flows is approximately four atoms. But what is most important to observe is that when current flows, it is not a single electron that flows from one end of a conductor to the other. All

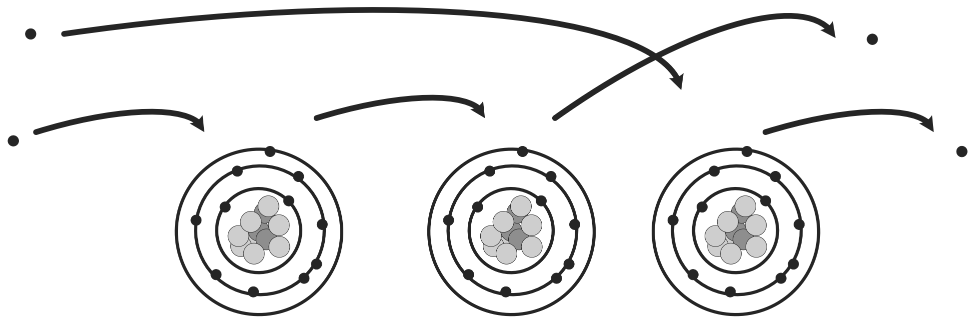


Figure 1-2 Electrons can travel through a conductor from one nucleus to another.

electrons tend to shift in the same direction. This is analogous to a train with many cars entering and leaving a long tunnel. The cars enter and leave the tunnel at the same rate, but it may be a considerable amount of time before an individual car that enters the tunnel leaves it again at the other end.

1.3 Insulators

Elements with several electrons in their valence band act like insulators. That is, they do not readily conduct current. This is not to say that they cannot conduct current under any condition. It actually means that it takes considerable energy (force) to dislodge electrons from the valence band (into what is often termed a conduction band) where electrons (current) can begin to flow. We say that the material has "broken down" when there is enough energy to get current flowing through it. Usually that means the energy has caused the material to change form.

A common example of this is wood. Wood is a very poor conductor of current and would normally be considered an insulator. But if enough energy is present—a lightning bolt, for example—current will flow through wood. The moisture content in the wood is a factor, and the wood changes form (burns) under this much energy. Nevertheless, this illustrates the point that in the presence of enough force or energy, an insulator can be made to conduct current.

1.4 Charge Field

Most of us learned in school that "like charges repel" and "unlike charges attract" each other. Every electron has a negative charge, and that charge is equal to every other electron's charge. Electrons, being of like charge, tend to repel each other. So, as shown in Figure 1-2, if one electron jumps into a valence band that is already occupied by another electron, it will tend to repel the other electron onward.

We might picture a charged particle as being a sphere, as shown in Figure 1-3. A charged particle radiates an electric field away from it that extends out in all directions. The strength of this field is inversely proportional to the square of the distance.

Suppose we have a surface (maybe a trace) with some "extra" electrons at a point along it. By "extra" I mean more electrons than would normally be contained in the atomic elements making up the trace. (We'll talk later about how we

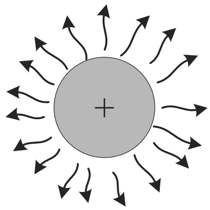


Figure 1-3 A charged particle has an electric field that radiates away from it in all directions.

might make that happen.[5]) Suppose we have another surface (maybe another trace) nearby with the same number of extra electrons on it. The extra electrons, being the same charge, will tend to repel one another.

Furthermore, they will do so with some force. The force might be very small, or it might be quite large, depending on the number of extra electrons. If the extra electrons are free to move, they may move away from each other, and in doing so, they would become moving electrons, or current. The force with which they repel one another is inversely proportional to the square of the distance between them, so by moving away from one another, the force is reduced.

If the electrons are not free to move, the force will still exist between them. If nothing moves, we call this a *static* force. If there is a force between two objects (or sets of objects), we can imagine that a force field exists between them. That force field is strongest along the shortest (most direct) line between them. The field weakens as we move farther away from this line. This field is called a *charge field* or an *electrical field*. Any time we have two charges separated by some distance, there will be a force field between them.

Now suppose we have the same situation as before, and the two sets of charges are not equal. If there are dissimilar charges, there will be a force between them that is attractive. That is, the two sets of charges will want to move toward each other.

It is very important to notice something here. The two sets of charges do not have to be opposite each other. That is, one set does not have to be negative and the other positive. The charge *difference* between two or more objects is a relative concept. We can have two negative sets of charges with one more negative than the other or two positive sets of charges with one more positive than the other.

5. One way might be to rub a surface with wool, creating a static charge on it.

There will be an attractive force in either case that will be proportional to the net difference in their total charge.

1.5 Magnetic Field

When electrons move (that is, when current flows), a magnetic field is generated around that current flow. This is the basis of an electromagnet. The magnetic field is normally oriented in concentric circles around the current flow, and (like an electric field) it decreases in strength inversely proportional to the square of the distance from the current flow. It is polarized, and its direction (toward its north pole) can be found by the right-hand rule: Point your thumb in the direction of the current flow, and the fingers of your right hand will curl in the direction of the field. See Figure 1-4.

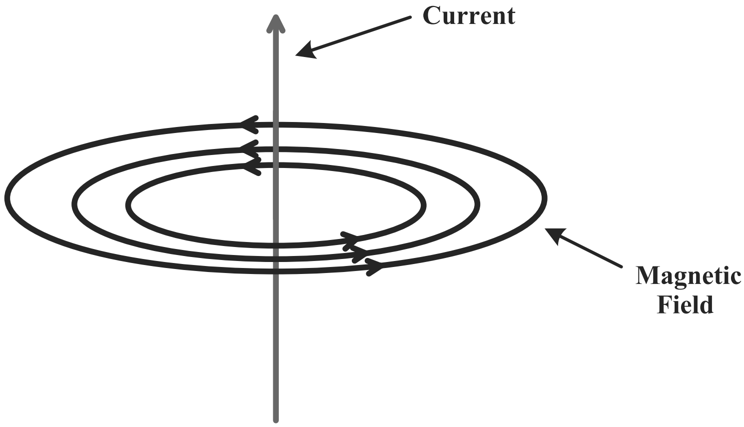
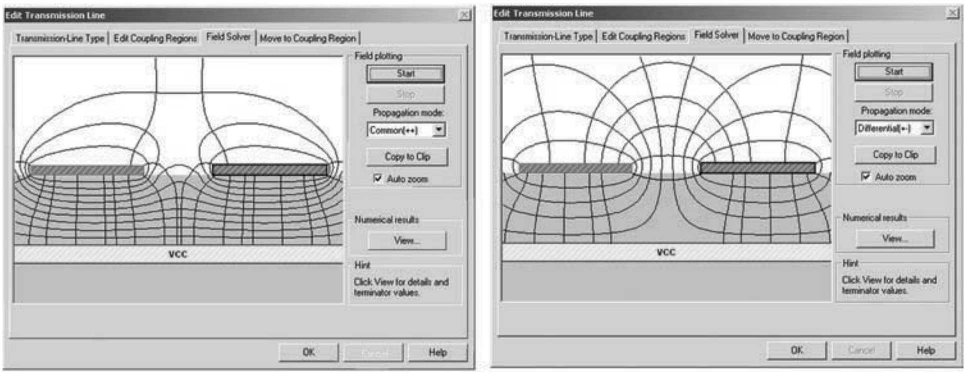


Figure 1-4 If current is flowing, there is a magnetic field around the current; the direction of the field can be found by the right-hand rule.

This magnetic field is well known to boaters and airplane pilots. It can be a significant safety problem if current paths related to radios or lights create magnetic fields that change the direction in which a compass points.[6]

6. Brooks describes a compass experiment that illustrates this in his book *Signal Integrity Issues and Printed Circuit Board Design* (Upper Saddle River, NJ: Pearson Education, Inc., 2003), 331.

When current flows (for example, on a circuit board trace), both of these fields (magnetic and electric) exist at the same time. Electric fields can radiate not only into space but also to adjacent traces or planes. Magnetic fields circulate around the trace(s). The pattern of the fields depends on the relative direction and magnitudes of currents on nearby traces. The Hyperlynx signal integrity tool from Mentor Graphics can illustrate these fields when traces are coupled together in the tool. Figure 1-5a illustrates a case of a pair of traces carrying differential signals (the signals are equal and opposite on the two traces). Figure 1-5b illustrates the common-mode case, where the signals are identical on both traces. Notice how the like charges and fields repel (a) and unlike charges and fields attract (b) each other.



(a) (b)

Figure 1-5 The Hyperlynx simulation tool can illustrate how the radial electric and circular magnetic fields form around a pair of coupled Microstrip traces above an underlying plane.

1.6 Forces Driving Current

Electrons do not flow (that is, current doesn't exist) without a driving force. Some force must move the electrons along from one point to another. In general, from a practical standpoint, the two categories of force that move electrons are a voltage, or a charge difference, between two points, and the presence of a changing magnetic field that causes electrons to flow. How these forces come into being is the question.

1.6.1 Batteries A common battery is an excellent example of a device that gives us a voltage (charge differential) at its terminals. The difference in charge comes about through a chemical reaction in the battery.[7] Charles Augustin de Coulomb (1736–1806) is credited with *Coulomb's Law* (1785), which states

> *There are two kinds of charge, positive and negative. Like charges repel, unlike attract, with force proportional to the product of their charge and inversely proportional to the square of their distance.*

Since there are unlike charges at each terminal of a battery (positive and negative), the charges are attracted from one terminal to the other. If we provide a path (circuit) through which the charge can flow, it will do so.

There are many different types of batteries, but the process is pretty similar for all of them. The electrodes (the positive and negative terminals) are dissimilar materials (usually some form of metal), and a chemical solution of some type (called an electrolyte) is between them. The electrolyte reacts (a process called an electrochemical reaction) with one or both of the electrodes to create at least one other compound and either some positive or negative ions. The ions are charged and provide the source of the charge for the battery. When the terminals of the battery are connected through a circuit, the electrons flow through the circuit to the other terminal/electrode, where they combine with the ions or compounds at that terminal.

Alessandro Volta (1745–1827) is credited with making the first battery in 1800. The measure of voltage is named after him (volt). He made his first battery with zinc and silver, with salt water as the electrolyte. Some common materials used in battery manufacture today include

- Zinc/carbon (standard carbon battery)
- Zinc/manganese-oxide (alkaline battery)
- Lithium-iodide/lead-iodide (lithium battery)
- Lead/lead-oxide (automotive battery)
- Nickel-hydroxide/cadmium (NiCad battery)
- Zinc/air

Each combination of materials and electrolytes produces a specific battery voltage (often ranging from a fraction of a volt to 1 or 2 volts). If more voltage is desired, more battery cells are placed in the series. For example, the automotive

7. A Web search on batteries will produce a large number of hits. One useful reference is http://science.howstuffworks.com/battery.htm.

lead acid battery produces approximately 2 volts per cell. A 12-volt car battery has six internal cells. Typically, the current capacity of an individual battery is a function of the surface area between the metals and the electrolytes. If you want more current capacity from an individual battery, you need larger cells. That's why standard battery sizes range from AAA to D. The chemical processes (and the voltage) are the same for each size, but the surface area is larger for larger physical sizes.

Batteries typically have a maximum charge flow (current flow) that they can provide. This is because as charge circulates through a circuit, additional charge (ions) must be made available at the terminals. Different electrochemical reactions differ at the rate at which they can provide charge. Batteries with plates with larger surface areas typically can provide more charge (current) at a specific point in time than can batteries with smaller plates.

In some batteries, the chemical process is reversible. Such batteries are rechargeable. If we circulate the charge from the battery through a circuit, we can then connect the battery to a charger (typically just a higher voltage) and restore the materials back to a charged condition. Other chemical processes are not reversible. These batteries will run down, or discharge, with use until the chemical process can no longer provide ions for the charge.

1.6.2 Generators The other common source of force for generating current comes from electrical generation. Michael Faraday (1791–1867) formulated *Faraday's Law of Magnetic Induction* (1831), which states that a *changing* magnetic field is accompanied by a changing electric field that is at right angles to the change of the magnetic field. We start with a magnetic field, which can come from a physical magnet or a current flowing through a conductor. In either of these cases, there is always a magnetic field. The most important word in Faraday's Law is *changing*. Consider the presence of another wire or trace nearby. There will be an electric field, and therefore an electric force, generated in this conductor if the nearby magnetic field is *changing.*

The changing nature of the magnetic field can be caused by one or more of several different factors. The physical magnet may be moving relative to the conductor, or the conductor may be moving in relation to the magnet. The current that is creating the magnetic field may be changing. Any of these situations will create a changing relationship between the adjacent conductor and the magnetic field. Thus, any of these situations can create an electric field, and therefore a current flow, in the adjacent wire.

This is the basic principle behind all generators. Typically a wire coil is turned in the presence of a magnet field, generating a force in the coil, or a magnetic field is changed near a coil. In dams and oil- or coal-fired (even nuclear) generation plants, the electrical power comes from generators where (typically) coils are turned in the presence of strong magnets. Current or voltage is generated in the secondary coil of a transformer by the changing magnetic field caused by a changing current through the primary winding of the transformer. Almost all electrical force in our homes and offices originates from generators.

1.6.3 Static Electricity We are all familiar with static electricity. That's what causes the spark to jump between our hand, for example, and another object or person. Static electricity represents the force between two points that have a different charge. It is often caused by rubbing two different (insulating) materials together. Electrons transfer from one material to the other, creating the charge imbalance.

If we connect a conductor between two points charged with static electricity, current will flow until the charge difference between them is neutralized. In most practical cases, the amount of charge imbalance is not too great. There may be a significant voltage difference because of the charge imbalance, but the total amount of charge is usually small. A small spark may jump when the voltage difference is high but the amount of accumulated charge is small. An example is when we walk on a carpet, and the motion of our shoes against the carpet creates a charge difference between our bodies and nearby objects. Then when we touch a doorknob, the charge difference results in a spark. The spark is, in fact, charge (electrons, and therefore current) jumping between our bodies and the doorknob. The spark can be a "shock," but it is over very quickly. In most practical cases, static electricity dissipates over time in the objects, or into the air, so the charge imbalance is not maintained for a long period of time.

For this reason, static electricity (static charge) is usually not a practical source of charge for current generation. Static discharge, however, can be destructive to electronic equipment. Although the total charge that jumps from one object to another may not be great, the initial charge spike caused by a high voltage, though brief, may be hot enough to burn, and therefore destroy, sensitive equipment. This can be a particular problem in semiconductors. Care must be taken to prevent static electricity sparks from traveling through a semiconductor junction. The localized heating, though small, may be enough to burn a hole through the junction and destroy it.

A common example of very large static electric charge differences is what occurs during an electrical storm. The static charge difference can be very high because the two objects being rubbed together (the earth and the atmosphere) are so large. When the charge difference gets high enough, a spark jumps between the objects, helping to neutralize the charge difference—in this case, lightning. Here, the voltage difference and the current magnitude are very large—large enough to be lethal.

The effects of a lightning strike also illustrate the limits of insulating materials. Wood, for example, is normally a pretty good insulator. But when lightning strikes a tree, the force (voltage) behind the strike is enough to change the state of the wood (it burns it) so that it becomes conductive.

1.7 Voltage versus Current

Let's say there are two terminals separated by a space. Assume one terminal has more charge relative to the other, so the charge between the terminals is different. Different charges attract each other with a force that is related to the magnitude of the charge difference. This force creates an electric field between the terminals.

The force between these two terminals is defined as voltage. If we connected the two terminals together with a conductor, charge would flow from one terminal to the other. That charge flow is defined as current. In general, current cannot flow without a force "pushing" it along. If the two terminals had exactly the same charge (no force or voltage between them) and we connected them together with a conductor, nothing would happen.

An ordinary garden hose is a good analogy. Say the hose is connected to a faucet that is turned off. This is like a wire connected to the positive terminal of a battery through a switch that is turned off. The other end of the hose is lying open on the ground. Now turn the faucet on.

There is water pressure at the faucet (analogous to voltage) that is much higher than the pressure at the other end of the hose. So water flows through the hose in a manner analogous to current flowing through a wire. If we disconnected the hose while there was still water in it and left it lying on level ground, there would be no force pushing the water out of the hose. But if we raised one end of the hose higher than other end, gravity would provide the force to drain any remaining water from the hose.

There is a very well-defined relationship between the voltage (force) between two points and the current that can flow between those two points, depending on the impedance to current of the path that connects those points. This relationship is called Ohm's Law, which is discussed in Chapter 3.

The nomenclature we use to define voltage and current can sometimes be confusing. For example, we say that a battery is a 9-volt DC (direct current) battery. This means the force at the battery terminal (absent a very heavy load) is 9 volts. But without a circuit between the two terminals, there is no current flow, direct or otherwise. The DC means that if and when we do connect a circuit between the terminals, current will only flow in one direction.

We often draw pictures of voltage and current waveforms without carefully distinguishing between them. We can get away with this because, at least with resistive circuits, the voltage and current waveforms look very much alike. But sometimes they don't. When creating or looking at pictures of waveforms, it is important to be clear about whether they are voltage waveforms or current waveforms.

1.8 Direction of Current Flow

Ben Franklin said that current flows from positive to negative. But you may have recognized by now that current is the flow of electrons, and negatively charged electrons would flow from negative to positive. This may be the only time that Ben was wrong, but his statement is still used today. By convention, whenever we analyze circuits and schematics, we think of current as flowing from positive to negative, the opposite of what is really happening.

It turns out that, in most cases, it doesn't make any difference. So we never bother to address this anomaly, and we just live with it. No harm is done. But there is one case where there is a real difference: current flow in semiconductors.

1.9 Semiconductor Hole Flow

Earlier we described good conductive elements as those having a single electron in their valence shell or band. Insulators had their valence bands nearly filled. There are certain elements, however, whose valence bands are exactly half filled with electrons. Silicon and germanium, for example, each have four valence electrons in a band that can contain eight electrons. These elements belong to a class we call *semiconductors*.

In general, semiconductors are poor conductors of current. But suppose, for example, we add a small amount of impurity to an otherwise pure silicon structure. Antimony, arsenic, and phosphorous are three examples of elements that have five electrons in their valence band. If we allow an atom of phosphorous, for example, to take the place of a silicon atom in an otherwise pure crystalline silicon structure, an "extra electron" results, as shown in Figure 1-6. It is not truly extra, but it is not as tightly held as all the other nearby electrons. When we add elements that contribute extra electrons to the structure, we call it "n-doping" ("n" for negative) and say we are creating an N-type semiconductor.

Similarly, boron, aluminum, and gallium each have only three electrons in their valence bands. If we allow an atom of aluminum, for example, to take the place of a silicon atom in an otherwise pure crystalline silicon structure, an "electron hole" results, also shown in Figure 1-6. Again, this is not really a shortage of an electron, but a nearby electron might be "captured" and held more tightly at this location than if the silicon structure were totally pure. We call this process "p-doping," creating a P-type semiconductor.[8]

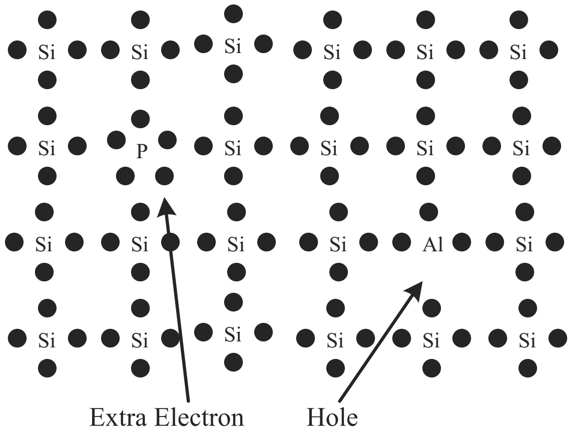


Figure 1-6 Impurities added to an otherwise pure silicon crystalline lattice can create extra electrons or electron holes.

Now imagine that the electron immediately to the left of the hole in Figure 1-6 moves to the right and fills the hole there. That then creates a hole where this electron used to be. This might happen if there were an external force (voltage) applied to the structure. Here is the philosophical question: Did the electron move to the right (electron flow), or did the hole move to the left (hole flow)? In one sense, this is just a philosophical question,[9] but certain

8. For a good discussion of doping, see http://hyperphysics.phy-astr.gsu.edu/hbase/solids/dope.html.
9. It should be noted that electron mobility (and therefore hole mobility) is different in different types of materials, especially different p-doped and n-doped semiconductors. This affects signal propagation times through the different materials. While this is beyond the scope of this book, I will note that not everyone would agree that hole flow versus electron flow is just a philosophical question!

phenomena are more easily explained from the standpoint of hole flow than from electron flow. Thus, the term *hole flow* is routinely used in semiconductor physics.

Sometimes people try to resolve the anomaly of current flowing from positive to negative in ordinary conductors, when the electrons are in fact flowing from negative to positive, by thinking in terms of hole flow instead. This can be appropriate in semiconductors, but there are no real holes in a copper structure. Electrons move because they are being pushed or pulled by an external force, not because there are holes to move into. Therefore, trying to extend the idea of hole flow to copper can just create more confusion. Personally, I prefer to live with the recognition that when it comes to conductors, it really doesn't matter much how we view it.

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