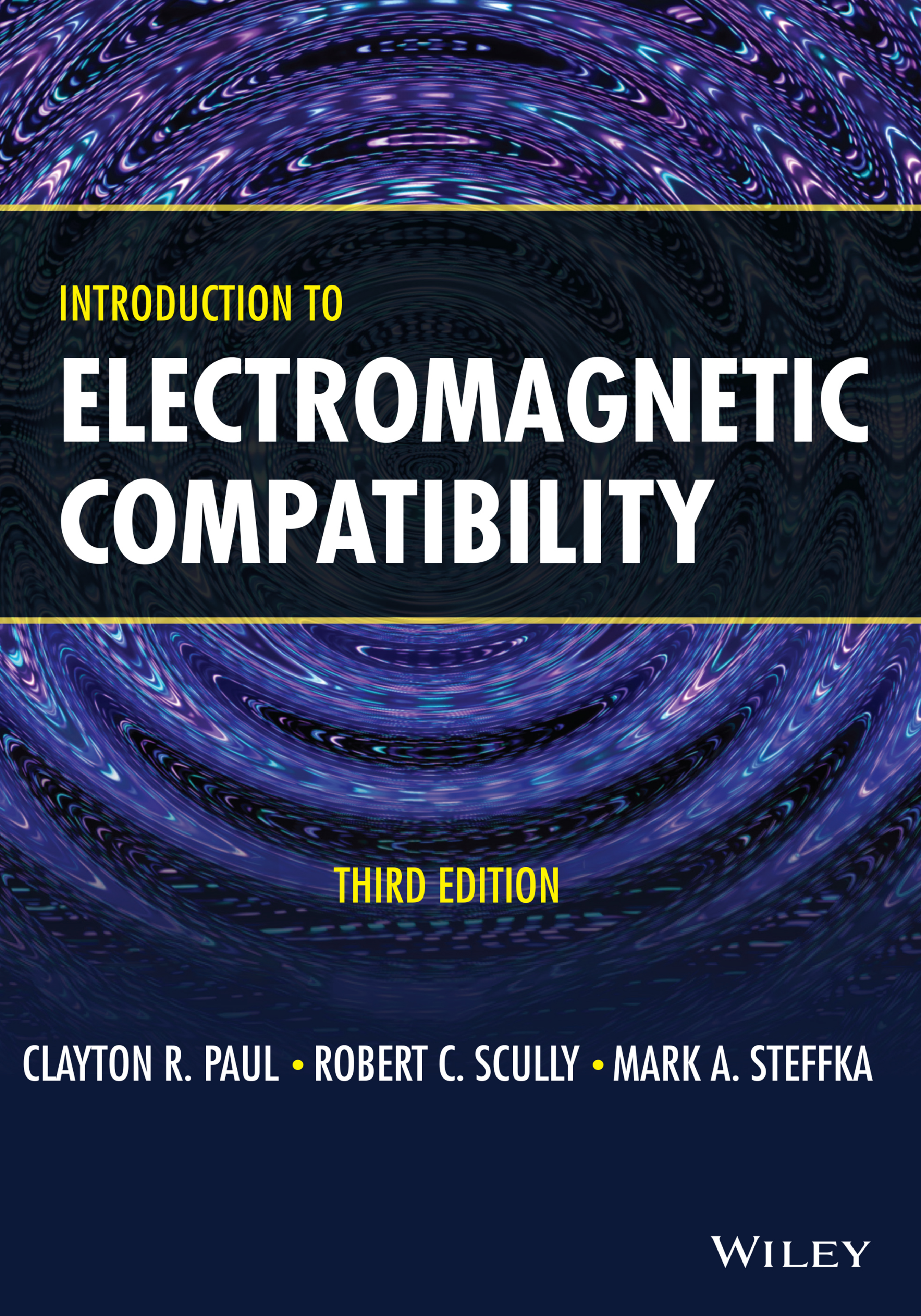

INTRODUCTION TO

ELECTROMAGNETIC COMPATIBILITY

THIRD EDITION

CLAYTON R. PAUL • ROBERT C. SCULLY • MARK A. STEFFKA

WILEY

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Preface

Nearly, 30 years have passed since our esteemed colleague, mentor, and friend, Dr. Clayton R. Paul first published his textbook *Introduction to Electromagnetic Compatibility*. One of, if not the, most thorough and highest quality texts of its kind, Dr. Paul's book has become in that nearly 30-year time frame one of the world's most well-known and most widely referenced works on EMC ever written.

Dr. Paul's work has more than survived the "test of time." The foundation he established has enabled two generations (and counting!) of researchers, engineers, and technicians, to not only successfully master the fundamentals of the EMC discipline but to confront the seemingly ever-increasing number of EMC requirements levied against all sorts of systems and products, from the largest power generation and distribution systems to the highly integrated and advanced technologies found in the billions of handheld devices in daily use around the world.

Given the stature and ageless character of Dr. Paul's work, with a strong and abiding sense of humility, it is our great honor and privilege to present this third edition of Dr. Paul's outstanding textbook *Introduction to Electromagnetic Compatibility*.

Our goal in editing this work was to undertake a detailed and critical evaluation of every aspect of the second edition, including the physical and mathematical principles and fundamentals necessary to the practice of the EMC discipline presented in the text, the many and varied analytical tools provided by Dr. Paul to assist in the understanding of the complexities and vagaries of EMC issues, and the plethora of examples used to emphasize and provide insight into the material content.

We are pleased to say we have met our goal and have determined that Dr. Paul's amazing ability to translate and apply his insight and knowledge of the relevant physics, mathematics, and circuit theory, to electrical and electronics systems' EMC remains as essential today as it was at the time of publication of the first edition, and as it will undoubtedly remain into the foreseeable future.

One of the areas that garnered our close attention was how to address the proliferation of computer circuit analysis tools such as SPICE and its many derivatives and iterations, along with the explosion of EMC and antenna modeling simulation tools, having occurred since Dr. Paul's original work. Dr. Paul was an early and staunch advocate of the use of such tools, and it is our opinion that Dr. Paul would be pleased with and highly supportive of their use. The abundance of such tools, however, was something of a two-edged sword for us, as it proved impossible to effectively incorporate the almost certainly countless examples of so many different tools in this text. We ultimately decided not to attempt to do so, electing to maintain the primary thrust of the text as a focused survey of all things EMC as Dr. Paul originally intended it. We did add some brief information regarding the use of antenna modeling tools in Chapter 7. We also elected to retain Appendix D that provides basic information on the use of SPICE, and to expand the Appendix with examples of some of Dr. Paul's excellent tutorials and applications excised from the main body of the text. We took the liberty of adding basic tutorial information for the use of LTSPICE, a freely available, more recent iteration of SPICE. This allowed us to reduce the number of “SPICE” examples in this edition (compared to previous ones) to encourage the reader to use SPICE, LTSPICE, or any other analytical tools with which they are most familiar, to explore and develop their own insight into those methods as applied to EMC analysis.

Many students and practitioners of the EMC discipline have struggled over time with numerical results and how to present them, or interpret them, from the perspective of the “right” number of significant digits to include, and a brief section discussing this important topic has been added to Chapter 1. The section on Power Loss in Cables was deleted in favor of entirely similar information originally included in Sections 4.5.2 through 4.5.4 of Chapter 4. All references in the various chapters were checked and revised as necessary, particularly for EMC standards cited in the text. It is expected those will continue to evolve and be updated many times during the useful lifetime of this edition of the textbook, and the reader is encouraged to keep track of such changes independently. The sections on the History of EMC and some illustrative examples in Chapter 1 have been relocated to Appendix E. Numerous editorial corrections were made to correct spelling, grammatical, and duplicative errors found throughout the text.

We would like to express our heartfelt thanks to our editors, Sarah Keegan and Sarah Lemore, both of whom exhibited seemingly unlimited patience working with us as we navigated this effort though job changes, retirements, relocations, pandemics, and other unexpected challenges. We would also like to thank our spouses for their unstinting support and understanding through long hours of keyboard sessions in the midst of all the foregoing trials and tribulations. We would also like to express our appreciation to Adam Fuchs, one of Mark Steffka’s recent students at the *University of Detroit - Mercy*, for his work in revising the content of Chapter 1 and developing the tutorial on the use of LTSPICE. Both of those tasks that he took on will certainly help the reader of this book.

Finally, although Dr. Paul’s physical presence with us sadly came to an end a few years ago, it is our fervent wish and desire that his work and legacy live on forever.

ROBERT C. SCULLY
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Canton, MI

December 2021

CHAPTER ONE

Introduction to Electromagnetic Compatibility (EMC)

Since the early days of radio and telegraph communications, it has been known that a spark gap generates electromagnetic waves rich in spectral content (frequency components) and that these waves can cause interference or noise in various electronic and electrical devices such as radio receivers and telephone communications. Numerous other sources of electromagnetic emissions such as lightning, relays, dc electric motors, and fluorescent lights also generate electromagnetic waves that are rich in spectral content and can cause interference in those devices. There are also sources of electromagnetic emissions that contain only a narrow band of frequencies. High-voltage power transmission lines generate electromagnetic emissions at the power frequency [60 Hz; 50 Hz in Europe]. Radio transmitters transmit desired emissions by encoding information (voice, music, etc.) on a carrier frequency. Radio receivers intercept these electromagnetic waves, amplify them, and extract the information that is encoded in the wave. Radar transmitters may transmit pulses of a single-frequency carrier or may transmit a band of frequencies using a chirp modulation scheme. The spectral content of such radar pulse transmissions is distributed over a larger band of frequencies around the carrier than are radio transmissions. Another important and increasingly significant source of electromagnetic emissions is associated particularly with digital computers, and digital electronic devices in general. These digital devices utilize pulses to signify a binary number, 0 (off) or 1 (on). Numbers and other symbols are represented as sequences of these binary digits. The transition time of the pulse from off to on and vice versa is perhaps the most important factor in determining the spectral content of the pulse. Fast (short) transition times generate a wider range of frequencies than do slower (longer) transition times. The spectral content of digital devices generally occupies a wide range of frequencies and can be a major contributor to electromagnetic interference in electrical and electronic devices.

This text is concerned with the ability of these types of electromagnetic emissions to cause *interference* in electrical and electronic devices. The reader has no doubt experienced noise produced in an AM radio by nearby lightning discharges. The lightning discharge is rich in frequency components, some of which pass through the input filter of the radio, causing noise to be superimposed on the desired signal. Also, even though a radio may not be tuned to a particular transmitter frequency, the transmission may be received, causing the reception of an unintended signal. These are

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examples of interference produced in *intentional receivers*. Of equal importance is the interference produced in *unintentional receivers*. For example, a strong transmission from an FM radio station or TV station may be picked up by a digital computer, causing the computer to interpret it as data or a control signal resulting in incorrect function of the computer. Conversely, a digital computer may create emissions that couple into a TV, causing interference.

This text is also concerned with the design of electronic systems such that interference from or to that system will be minimized. The emphasis will be on *digital* electronic systems. An electronic system able to function compatibly with other electronic systems and not produce or be susceptible to interference is said to be *electromagnetically compatible* with its environment. The objective of this text is to learn how to design electronic systems for *electromagnetic compatibility* (EMC). A system is electromagnetically compatible with its environment if it satisfies three criteria:

1. It does not cause interference with other systems.
2. It is not susceptible to emissions from other systems.
3. It does not cause interference with itself.

Designing for EMC is not only important for the desired functional performance; the device must also meet *legal* requirements in virtually all countries of the world before it can be sold. Designing an electronic product to perform a new and exciting function is a waste of effort if it cannot be placed on the market!

EMC design techniques and methodology have become an integral part of the design of electrical and electronic devices and systems. Consequently, the material in this text has become a fundamental part of an electrical engineer's background. This will no doubt increase in importance as the trend toward increased clock speeds and data rates of digital systems continues.

This text is intended for a university course in electromagnetic compatibility in an undergraduate/graduate curriculum in electrical engineering. There are textbooks available that concern EMC, but these are designed primarily for the industrial professional. Consequently, we will draw on a number of sources for reference material. These will be given at the end of each chapter, and their reference will be denoted in the text by brackets (e.g., [xx]). Numerous trade journals, EMC conference proceedings, and the *Institute of Electrical and Electronics Engineers* (IEEE) *Transactions on Electromagnetic Compatibility* contain useful tutorial articles on various aspects of EMC that we will discuss, and these will similarly be referenced where appropriate. The most important aspect in successfully dealing with EMC design is to have a sound understanding of the basic principles of electrical engineering (circuit analysis, electronics, signals, electromagnetics, linear system theory, digital system design, etc.). We will therefore review these basics so that the fundamentals will be understood and can be used effectively and correctly by the reader in solving the EMC problem. A representative set of such basic texts is [1–3]. A representative but not exhaustive list of texts that cover the general aspects of EMC is represented by [4–13]. The text by Ott [4] will form our primary EMC text reference. Other texts and journal articles that cover aspects of EMC will be referenced in the appropriate chapters. Textbooks on the design of high-speed digital systems are represented by [14–16]. For a discussion of the evolution of this EMC course, see [17, 18].

1.1 ASPECTS OF EMC

As illustrated above, EMC is concerned with the *generation, transmission*, and *reception* of electromagnetic energy. These three aspects of the EMC problem form the basic framework of any EMC design. This is illustrated in Fig. 1.1. A *source* (also referred to as an *emitter*) produces the emission, and a *transfer* or *coupling path* conveys the emission energy to a *receptor (receiver)*, where it is

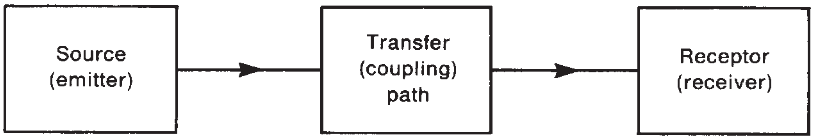

FIGURE 1.1 The basic decomposition of the EMC coupling problem.

processed, resulting in either desired or undesired behavior. Coupling, referred to often in this text, is the desired or undesired transfer of energy from one medium to another. Examples of coupling include capacitive coupling, inductive coupling, or even something as simple as a copper wire connecting two devices. *Interference occurs if the received energy causes the receptor to behave in an undesired manner*. Transfer of electromagnetic energy occurs frequently via unintended coupling modes. However, the unintentional transfer of energy causes interference only if the received energy is of sufficient magnitude and/or spectral content to cause the receptor to behave in an undesired fashion. *Unintentional transmission or reception of electromagnetic energy is not necessarily detrimental; undesired behavior of the receptor constitutes interference*. So the *processing of the received energy* by the receptor is an important part of the question of whether interference will occur. Quite often it is difficult to determine, a priori, whether a signal that is incident on a receptor will cause interference in that receptor. For example, clutter on a radar scope may cause a novice radar operator to incorrectly interpret the desired data, whereas the clutter may not create problems for an operator who has considerable experience. In one case we have interference and in the other we do not, although one could argue that the receptor is the radar operator and not the radar receiver. This points out that it is often difficult to uniquely identify the three aspects of the problem shown in Fig. 1.1!

It is also important to understand that a source or receptor may be classified as intended or unintended. In fact, a source or receptor may behave in both modes. Whether the source or the receptor is intended or unintended *depends on the coupling path, as well as the type of source or receptor*. As an example, a radio station transmitter whose transmission is picked up by a radio receiver that is tuned to that carrier frequency constitutes an intended emitter. On the other hand, if the same radio transmission is processed by another radio receiver that is not tuned to the carrier frequency of the transmitter, then the emission is unintended. (Actually the emission is still intended but the coupling path is not.) There are some emitters whose emissions can serve no useful purpose. An example is the (nonvisible) electromagnetic emission from a fluorescent light.

This suggests that there are three ways to prevent interference:

1. Suppress the emission at its source.
2. Make the coupling path as inefficient as possible.
3. Make the receptor less susceptible to the emission.

As we proceed through the examination of the EMC problem, these three alternative solutions should be kept in mind. The "first line of defense" is to suppress the emission as much as possible at the source. For example, we will find that fast (short) rise/falltimes of digital pulses are the primary contributors to the high-frequency spectral content of these signals. In general, the higher the frequency of the signal to be passed through the coupling path, the more efficient the coupling path. So we should slow (increase) the rise/falltimes of digital signals as much as possible. However, the rise/falltimes of digital signals can be increased only to a point at which the digital circuitry malfunctions. Reducing the high-frequency spectral content of an emission tends to inherently reduce the efficiency of the coupling path and hence reduces the signal level at the receptor. There are "brute force" methods of reducing the efficiency of the coupling path that we will discuss. For example, placing the receptor in a metal enclosure (a shield) will serve to reduce the efficiency of the coupling path. Shielded enclosures are more expensive than reducing the rise/falltime of the emitter, and in practice, their actual performance in an installation may be far less than ideal. Reducing the susceptibility of the receptor is quite often difficult to implement and still preserve the desired function of the product. An example of implementing reduced susceptibility of a receptor to noise would be the use of error-correcting codes in a digital receptor. Although undesired electromagnetic energy is incident on the receptor, the error-correcting codes may allow the receptor to function properly in the presence of a potentially troublesome signal. If the reader will think in terms of reducing the coupling by working from left to right in Fig. 1.1, success will usually be easier to achieve and with less additional cost to the system design. Minimizing the cost added to a system to make it electromagnetically compatible is highly desirable and is an important consideration in EMC design. One can put all electronic products in metallic enclosures and power them with internal batteries, but the product appearance, utility, and cost would very likely be unacceptable to the customer.

We may further break the transfer of electromagnetic energy as it pertains to the prevention of interference, into four subgroups: *radiated emissions, radiated susceptibility, conducted emissions*, and *conducted susceptibility*, as illustrated in Fig. 1.2. A typical electronic system usually consists of one or more subsystems that communicate with each other via cables (bundles of wires). A means for providing power to these subsystems may be a commercial ac (alternating current) power system connected to the installation site. One or more power supplies in a typical electronic system converts the available ac power (may be 120 V, 60 Hz voltage in the US, or 240 V, 50 Hz in Europe) to the various dc (direct current) voltage levels required to power the internal electronic components of the system. For example, 3.3 Vdc to 5 Vdc may be required to power the digital logic, +12 Vdc, and − 12 Vdc voltages may be required to power analog electronics. Other dc voltages may be required to power devices such as motors. Sometimes the input ac power itself may be required to power other components such as small cooling fans. The ac system power is obtained from the commercial power net via a line cord. Other cables are required to interconnect subsystems so that functional signals can be passed between them. All these cables have the potential for emitting and/or picking up electromagnetic energy and are usually quite efficient in doing so. Generally speaking, the longer the cable, the more efficient it is in emitting or picking up electromagnetic energy. Interference signals can also be passed directly between the subsystems via direct conduction on these cables. If the subsystems are enclosed in metallic enclosures, currents may be induced on these enclosures by external signals or internal signals. These induced currents can then radiate to the external environment or to the interior of the enclosure. It is becoming more common, particularly in low-cost systems, to use nonmetallic enclosures, fabricated from non-conductive plastic or composite materials. The electronic circuits contained in these nonmetallic enclosures are, for the most part, completely exposed to electromagnetic emissions, and as such can directly radiate or be susceptible to these emissions. The four aspects of the EMC problem, *radiated emissions, radiated susceptibility, conducted emissions*, and *conducted susceptibility*, illustrated in Fig. 1.2, envelope these considerations.

Electromagnetic emissions can occur from the ac power cord, a metallic enclosure containing a subsystem, a cable connecting subsystems or from an electronic component within a nonmetallic enclosure as Fig. 1.2a illustrates. It is important to understand that “currents radiate.” The fundamental process that produces radiated emissions is the acceleration of charge. A time-varying current comprises accelerated charge. Throughout the text we will be trying to replace certain misconceptions that prevent an understanding of this fundamental process. One example is the notion that an ac power cord carries only low-frequency power system signals. Although the primary intent of this cable is to transfer commercial ac power to the system, it is important to realize that *other much higher-frequency signals may and usually do exist on the ac power cord*! These are coupled to the ac power cord from the internal subsystems via a number of coupling paths that we will discuss. Once these higher-frequency currents couple onto this long (typically 1 m or more) cable, they will radiate

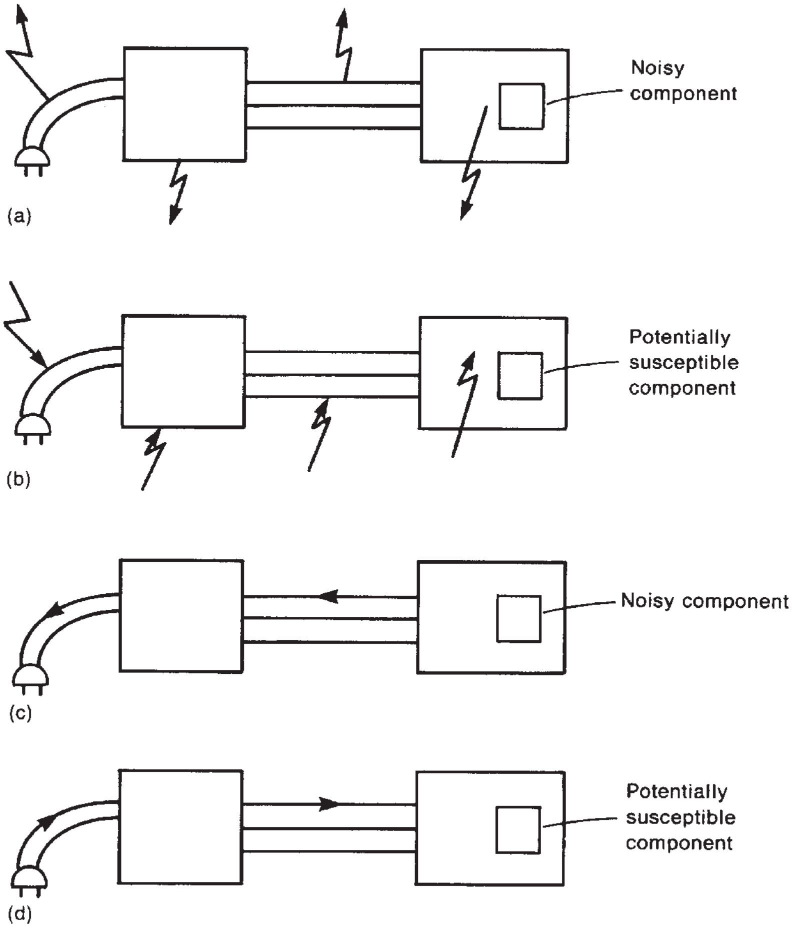

FIGURE 1.2 The four basic EMC subproblems: (a) radiated emissions; (b) radiated susceptibility; (c) conducted emissions; (d) conducted susceptibility.

into the surrounding space quite efficiently. Also, this long cable may function as an efficient "antenna" and pick up radiated emissions from other nearby electronic systems as shown in Fig. 1.2b. Once these external signals are induced onto this cable, as well as any other cables connecting the subsystems, they may be transferred to the internal components of the subsystems, where they may cause interference in those circuits. To summarize, undesired signals may be radiated or picked up by the ac power cord, interconnection cables, metallic cabinets, or internal circuitry of the subsystems, even though these structures or wires are not intended to carry the signals.

Emissions of and susceptibility to electromagnetic energy occur not only by electromagnetic waves propagating through air but also by direct conduction on metallic conductors as illustrated in Fig. 1.2c and d. Usually this coupling path is inherently more efficient than the air coupling path. Electronic system designers realize this, and intentionally place barriers, such as filters, in this path to block the undesired transmission of this energy. It is particularly important to realize that the interference problem often extends beyond the boundaries shown in Fig. 1.2. For example, interference currents conducted out the ac power cord will flow into the power distribution net of the installation. This power distribution net is an extensive array of wires that are directly connected and as such may radiate these signals quite efficiently. In this case, a *conducted emission* produces a *radiated emission*. Consequently, restrictions on the emissions conducted out the product's ac power cord are intended to reduce the radiated emissions from this power distribution system.

Our primary concern will be the design of electronic systems so that they will comply with the *legal* requirements imposed by governmental agencies, or self-imposed limitations by companies in niche markets such as aerospace or automotive manufacturing. Some consumer electronics which traditionally fell into one EMC standard category now might blur the lines between different standards, such as smart appliances. However, there are also a number of other important EMC concerns

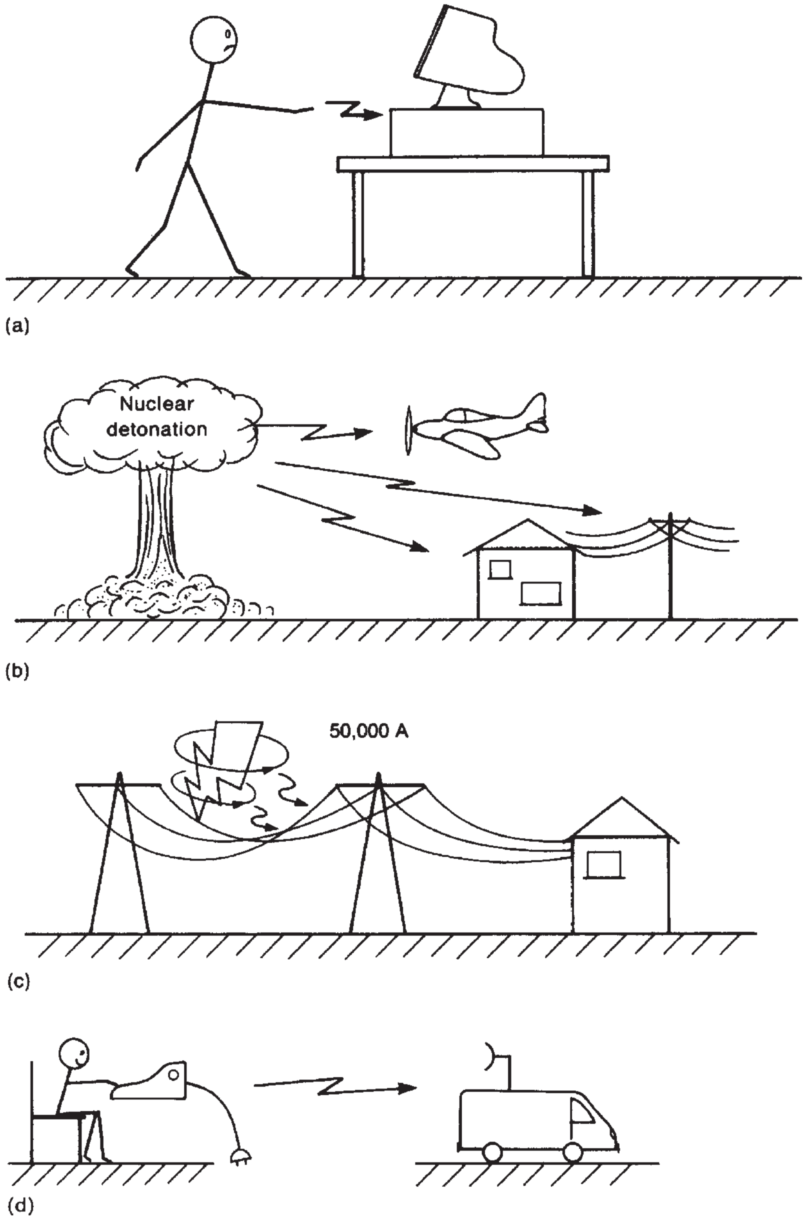

FIGURE 1.3 Other aspects of EMC: (a) electrostatic discharge (ESD); (b) electromagnetic pulse (EMP); (c) lightning; (d) TEMPEST (secure communication and data processing).

that we will discuss. Some of these are depicted in Fig. 1.3. Figure 1.3a illustrates an increasingly common susceptibility problem for today's small-scale integrated circuits, *electrostatic discharge* (ESD). Walking across a nylon carpet with rubber-soled shoes can cause a buildup of static charge on the body. If an electronic device such as a keyboard is touched, this static charge may be transferred to the device, and an arc is created between the fingertips and the device. The direct transfer of charge can cause permanent destruction of electronic components such as integrated circuit chips. The arc also bathes the device in an electromagnetic wave that is picked up by the internal circuitry. This can result in system malfunction. ESD is a very pervasive problem today.

After the first nuclear detonation in the mid-1940s, it was discovered that the semiconductor devices (a new type of amplifying element) in the electronic systems that were used to monitor the effects of the blast were destroyed. This was not due to the direct physical effects of the blast but was caused by an intense electromagnetic wave created by the charge separation and movement within the detonation as illustrated in Fig. 1.3b. Consequently, there is significant interest within the military communities in "hardening" communication and data processing facilities against the effect of this *electromagnetic pulse* (EMP). The concern is not with the physical effects of the blast but with the inability to direct retaliatory action if the communication and data processing facilities are rendered nonfunctional by the EMP. EMP effects can be created by smaller sources that do not require the use of nuclear detonations. Commercial industry, in particular the power industry, is now becoming much more interested in this phenomenon. Nefarious uses have been made of suitcase-sized transmitters that can damage localized targets, and the power industry is concerned about wide-scale effects of outages traced back to EMP events. This represents a radiated susceptibility problem. We will find that the same principles used to reduce the effect of radiated emissions from neighboring electronic systems also apply to this problem, but with larger numbers.

Lightning occurs frequently and direct strikes illustrated in Fig. 1.3c are obviously important. However, the indirect effects on electronic systems can be equally devastating. The "lightning channel" carries upward of 200,000 A of current. The electromagnetic fields from this intense current can couple to electronic systems either by direct radiation or by coupling to the commercial power system and subsequently being conducted into the device via an ac power cord. Consequently, it is important to design and test the product for its immunity to transient voltages on the ac power cord. Most manufacturers inject "surges" onto the ac power cord and design their products to withstand these and other undesired transient voltages that may appear at the entry point of ac power.

It has also become of interest to prevent the interception of electromagnetic emissions by unauthorized persons. It is possible, for example, to determine what is being typed on an electronic typewriter by monitoring its electromagnetic emissions as illustrated in Fig. 1.3d. There are also other instances of direct interception of radiated emissions from which the content of the communications or data can be determined. Obviously, it is imperative for the military to contain this problem, which it refers to as TEMPEST. The commercial community is also interested in this problem from the standpoint of preserving trade secrets, the knowledge of which could affect the competitiveness of the company in the marketplace.

There are several other related problems that fit within the purview of the EMC discipline. It is important to realize that these can all be viewed in terms of the four basic subproblems of radiated emissions, radiated susceptibility, conducted emissions, and conducted susceptibility shown in Fig. 1.2. Only the context of the problem changes.

The primary vehicle used to understand the effects of interference is a *mathematical model*. A mathematical model quantifies our understanding of the phenomenon and also may bring out important properties that are not so readily apparent. An additional, important advantage of a mathematical model is its ability to aid in the design process. *The criterion that determines whether the model adequately represents the phenomenon is whether it can be used to predict experimentally observed results*. If the predictions of the model do not correlate with experimentally observed behavior of the phenomenon, it is useless. However, our ability to solve the equations resulting from the model and extract insight from them quite often dictates the approximations used to construct the model. For example, we often model nonlinear phenomena with linear, approximate models.

Calculations will be performed quite frequently, and correct *unit conversion* is essential. Although the trend in the international scientific community is toward the metric or SI system of units, there is still the need to use other systems. One must be able to convert a unit in one system to the equivalent in another system, as in an equation where certain constants are given in another unit system. A simple and flawless method is to multiply by unit ratios between the two systems *and* cancel the unit names to ensure that the quantity should be multiplied rather than divided and vice versa. This method for converting units is known as dimensional analysis. For example, the units of distance in the English system (used extensively in the USA) are inches, feet, miles, yards, etc. Some representative conversions are 1 in. = 2.54 cm, 1 mil = 0.001 in., 1 ft = 12 in., 1 m = 100 cm, 1 mile = 5280 ft, 1 yard = 3 ft, etc. For example, suppose we wish to convert a distance of 5 miles to kilometers. We would multiply by unity ratios as follows:

$$5\text{ mi} \times \frac{5280\text{ ft}}{1\text{ mi}} \times \frac{12\text{ in.}}{1\text{ foot}} \times \frac{2.54\text{ cm}}{1\text{ in.}} \times \frac{1\text{ m}}{100\text{ cm}} \times \frac{1\text{ km}}{1000\text{ m}} = 8.047\text{ km}$$

Cancelation of the unit names in this conversion avoids the improper multiplication (division) of a unit ratio when division (multiplication) should be used. The inability to properly convert units is a leading reason for numerical errors. Note this text, as do many other technical resources, utilizes rounding to simplify calculations. When working on review exercises and problems, if the reader calculates an answer that does not resemble the book's answer, it is likely a rounding error was made at some point. Many of the problems presented in this text depend on the use of a calculator. It is recommended to use a graphing calculator's features to carry over as many decimal points as possible in calculations.

Review Exercise 1.1 Convert the following dimensions to those indicated: (a) 10 ft. to meters, (b) 50 cm to inches, (c) 30 km to miles.

***Answers*:** (a) 3.048 m (meters), (b) 19.685 in. (inches), (c) 18.64 mi (miles).

Note that each of these results may be rounded off, based on the appropriate number of significant digits as (usually) determined by the corresponding standard error. For example, in converting from feet to meters, the number of feet in a meter may be expressed as 3.28, 3.2808, or 3.281. Using these values, the result may be 3.04878, 3.04804, or 3.04785. The number of significant digits used in the calculation for the number of feet in a meter will dictate the number of significant digits in the final result. If 3.28 is used, the result should have 2 digits after the decimal point. If 3.2808 is used, the final result should have 4 digits after the decimal point. If 3.281 is used, the final result should have 3 digits after the decimal point. In all cases, if desired, the final result should be rounded off using standard rules.

Before we set out the standard rules for rounding off, let us agree on what to call the various components of a numeric value.

- The most significant digit is the left most digit (not counting any leading zeros which function only as placeholders and are never significant digits).
- If you are rounding off to n significant digits, then the least significant digit is the nth digit from the most significant digit. The least significant digit can be a zero.
- The first nonsignificant digit is the n + 1th digit.

Rounding-off rules

- If the first nonsignificant digit is less than 5, then the least significant digit remains unchanged.
- If the first nonsignificant digit is greater than 5, the least significant digit is incremented by 1.
- If the first nonsignificant digit is 5, the least significant digit can be either incremented or left unchanged (see below!)
- All nonsignificant digits are removed.

Finally, it is important to "sanity-check" any calculations done with a calculator. For example, 10 cm is approximately 4 in. (3.94 in.).

1.2 ELECTRICAL DIMENSIONS AND WAVES

Perhaps the most important concept that the reader should grasp in order to be effective in EMC is that of the *electrical dimensions* of an electric circuit or electromagnetic radiating structure (intentional or unintentional). *Physical dimensions of a radiating structure such as an antenna are not important,* per se*, in determining the ability of that structure to radiate electromagnetic energy. Electrical dimensions of the structure in wavelengths are more significant in determining this*. Electrical dimensions are measured in *wavelengths*. A *wavelength* represents the distance that a single-frequency, sinusoidal electromagnetic wave must travel in order to change phase by 360°. Strictly speaking, this applies to one type of wave: the uniform plane wave. However, other types of waves have similar characteristics, and so this concept has broad application. Appendix B contains a thorough but brief discussion of electromagnetic laws and principles as well as the uniform plane wave and wavelength. All electrical engineering undergraduate curricula require at least one semester of electromagnetic field theory that the material in Appendix B represents. The reader is strongly advised to review this important material in Appendix B or consult [1, 2].

Although Maxwell's equations govern all electrical phenomena, they are quite complicated, mathematically. Hence we use, where possible, simpler approximations to them such as lumped-circuit models and Kirchhoff's laws. The important question here is when we can use the simpler lumped-circuit models and Kirchhoff's laws instead of Maxwell's equations when analyzing a problem. The essence of the answer is when the largest dimension of the circuit is *electrically small*, for example, much smaller than a wavelength at the excitation frequency of the circuit sources. Typically, we might use the criterion that a circuit is electrically small when the largest dimension is smaller than one-tenth of a wavelength.

This notion of electrical dimensions and lumped-circuit models has other significant aspects that we must discuss. Electromagnetic phenomena are truly a *distributed-parameter* process in that the properties of the structure such as capacitance and inductance are, in reality, distributed throughout space rather than being lumped at discrete points. When we construct lumped-parameter electric circuit models, we are ignoring the distributed nature of the electromagnetic fields. For example, consider a lumped-circuit element such as a resistor and its associated *connection leads* as shown in Fig. 1.4. When using lumped-circuit models, we are in effect saying that the connection leads of the elements are of no consequence and their effects may be ignored. When is this valid? In Fig. 1.4, we have shown the element current (assumed cosinusoidal) that enters the left connection lead and exits the right connection lead as a function of time t. This current is actually a wave propagating with velocity v. If the medium surrounding the connection leads (wires) is air, the velocity of propagation

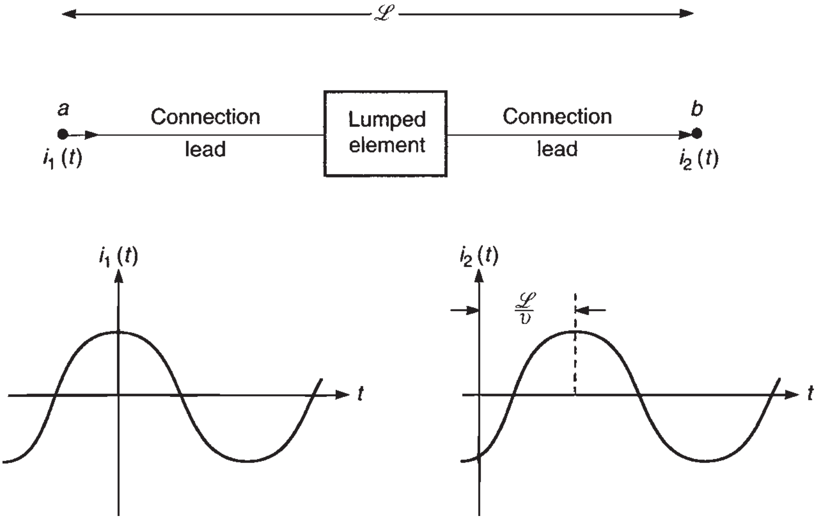

FIGURE 1.4 Illustration of the effect of element interconnection leads.

is the speed of light or $v_0 = 2.99792458 \times 10^8$ m/s or approximately $v_0 \cong 3 \times 10^8$ m/s. Because of this propagation, there is a finite *time delay*

$$T_D = \frac{L}{v} \text{ s} \tag{1.1}$$

required for the current wave to transit element *and* the connection leads and L is the total length of the element and its connection leads. For example, the time delay for a wave propagating in free space (approximately air) over a distance 1 m is approximately 3 ns or about 1 ns per foot. This time delay of propagation is becoming more critical in today's digital electronic circuits because of the ever-increasing speeds (and consequently the higher frequency content) of those digital signals. For example, in the mid-1980s or so the clock speeds of digital devices were on the order of 10 MHz. These digital signals had rise/falltimes in transitioning from a 1 to a 0 and vice versa on the order of 20 ns. Today the clock speeds of personal computers are on the order of 3 GHz or higher and the transition times are on the order of 100–500 ps or less. The velocity of propagation along a printed circuit board (PCB) land that interconnects the components is reduced from that of free space by the presence of the board material that is glass epoxy (FR-4) and is on the order of 1.8×10^8 m/s. Hence, the delay in transiting a 6-in. land on that PCB is on the order of 850 ps. Today this propagation delay can be on the order of the rise/falltimes of the digital signal and can cause timing problems in the digital logic. In the mid-1980s, it was insignificant, and the delay in transiting the digital gates was the only significant delay problem. Today the interconnect connections are drastically impacting *signal integrity*, which we will discuss in Chapter 4. We can look forward to this delay caused by interconnections to become even more critical to the performance of the digital device as clock and data speeds continue to increase seemingly without bound.

Suppose that the current and the associated wave are sinusoidal. Appendix B shows that a sinusoidal propagating wave can be written as a function of time t and position z as (where we have arbitrarily chosen a cosine form)

$$i(z, t) = I \cos(\omega t - \beta z) \tag{1.2}$$

where β is the *phase constant* in radians per meter (rad/m) and $\omega = 2\pi f$, where f is the cyclic frequency in Hz. This is shown in Fig. 1.5 as a function of distance z for fixed times t. As the wave

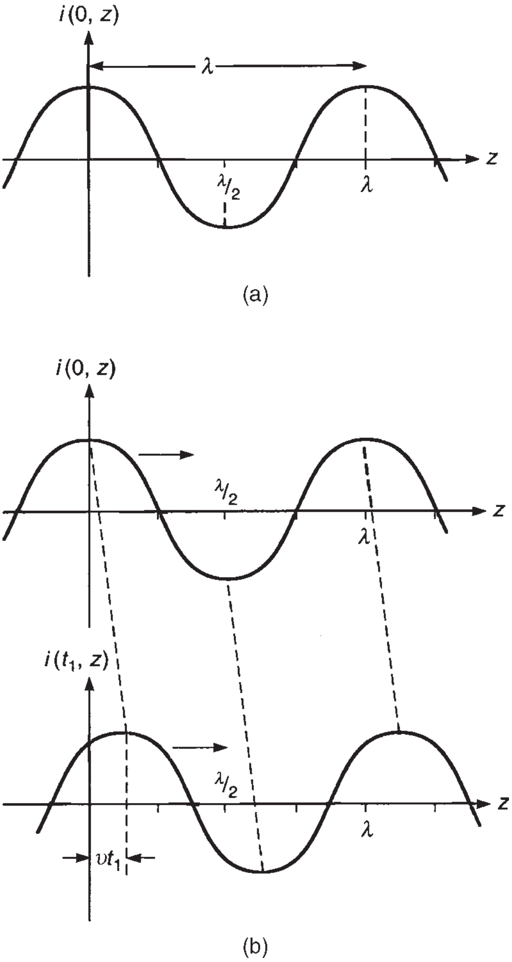

FIGURE 1.5 Wave propagation: (a) wave propagation in space and wavelength; (b) wave propagation as time progresses.

propagates from one end of the connection lead, through the element, and exists the other end of the other connection lead it suffers a *phase shift*, which is given in (1.2) by

$$\varphi = \beta L \,\text{rad} \tag{1.3}$$

and L is the total length of the connection leads. The phase shift is alternatively related to wavelength, which is denoted by λ and is *the distance that the wave must travel to change phase by* 2π *radians, which is equivalent to* 360°. Hence, the wavelength and the phase constant are related by

$$\beta\lambda = 2\pi \quad \text{rad} \tag{1.4}$$

Therefore, (1.2) can be written alternatively as

$$i(z,t) = I\cos\left(\omega t - \frac{2\pi}{\lambda}z\right) \tag{1.5}$$

Because distance z appears in this current expression as a ratio with wavelength λ, it becomes clear that physical distance z is not the important parameter; electrical distance in wavelengths z/λ is the critical parameter.

The wavelength of the wave is the distance between successive corresponding points such as the crest of the wave as shown in Fig. 1.5a. For the sinusoidal wave in (1.2), this means that we track points where the argument of the cosine remains constant:

$$(\omega t - \beta z) = \left(\omega t - \frac{2\pi}{\lambda} z\right) = \text{constant} \tag{1.6}$$

It is also clear that the wave in (1.2) is traveling in the $+z$ direction since as time t increases, distance z must also increase to keep the argument of the cosine constant in order to track the movement of a point on the waveform. Differentiating (1.6) gives the velocity of the wave movement as

$$\begin{aligned} v &= \frac{dz}{dt} \\ &= \frac{\omega}{\beta} \\ &= \lambda f \ \frac{\text{m}}{\text{s}} \end{aligned} \tag{1.7}$$

Hence, the wavelength can be written as

$$\lambda = \frac{v}{f} \ \text{m} \tag{1.8}$$

Table 1.1 gives the wavelengths of sinusoidal waves propagating in free space for various frequencies of that wave. Substituting (1.7) into (1.2) yields

$$\begin{aligned} i(z, t) &= I \cos\left(\omega\left(t - \frac{\beta}{\omega} z\right)\right) \\ &= I \cos\left(\omega t - \frac{z}{v}\right) \end{aligned} \tag{1.9}$$

This result illustrates that *the phase shift of a wave is equivalent to time delay*, which is given by z/v seconds.

From (1.3) and (1.4) as the current propagates along the connection leads a distance of one wavelength, $L = \lambda$, it suffers a phase shift of $\varphi = \beta\lambda = 2\pi$ radians or 360°. In other words, if the total length of the connection leads is one wavelength, the current entering the connection leads and the current exiting those leads are in phase but have changed phase 360° in the process of transiting the element. On the other hand, if the total length of the connection leads is one-half wavelength ($L = \lambda/2$), then the current suffers a phase shift of 180° so that the current entering the connection leads and the current exiting those leads are completely *out of phase*. If the length of the connection leads is 0.1 λ, the current suffers a phase shift of 36°. Over a distance of 0.05 λ, it suffers a phase shift of 18°, and over a distance of 0.01 λ it suffers a phase shift of 3.6°. If the effects of the connection leads are to be unimportant as is assumed by the lumped-circuit model, then the total length of the connection leads must be such that this phase shift is negligible. There is no fixed criterion for this, but we will assume that the phase shift is negligible if the lengths are smaller than,

TABLE 1.1 Frequencies of Sinusoidal Waves and Their Corresponding Wavelengths in Free Space (Air)

Frequency (f)	Wavelength (λ)
60 Hz	3107 mi (5000 km)
3 kHz	100 km
30 kHz	10 km
300 kHz	1 km
3 MHz	100 m
30 MHz	10 m
300 MHz	**1 m**
3 GHz	10 cm
30 GHz	1 cm
300 GHz	1 mm

say, 0.1 λ at the excitation frequency of the source. For some situations, the phase shift must be smaller than this to be negligible. Physical dimensions are not as important as *electrical dimensions* in determining the behavior of an electric circuit or device. Electrical dimensions are the physical dimensions in wavelengths. A physical dimension that is smaller than 0.1 λ is said to be *electrically small* in that the phase shift as a wave propagates across that dimension may be ignored. These concepts give rise to the rule of thumb that lumped-circuit models of circuits are an adequate representation of the physical circuit so long as the largest *electrical dimension* of the physical circuit is less than 0.1 λ. Table 1.2 gives the frequencies and corresponding wavelengths for various applications.

TABLE 1.2 Frequencies and Corresponding Wavelengths of Electronic Systems

Frequency Band[a]	Wavelength	Uses
EHF (30–300 GHz)	1 cm–1 mm	Radar, remote sensing, radio astronomy
SHF (3–30 GHz)	10 cm–1 cm	Radar, satellite communication, remote sensing, microwave electronic circuits, aircraft navigation, **digital systems**
UHF (300–3000 MHz)	1 m–10 cm	Radar, TV, microwave ovens, air navigation, cell phones, military air traffic control communication and navigation, **digital systems**
VHF (30–300 MHz)	10 m–1 m	TV, FM broadcasting, police radio, mobile radio, commercial air traffic control (ATC) communication and navigation, **digital systems**
HF (3–30 MHz)	100 m–10 m	Shortwave radio (ham), citizens band
MF (300–3000 kHz)	1 km–100 m	AM broadcasting, maritime radio, ADF direction finding
LF (30–300 kHz)	10 km–1 km	Loran long-range navigation, ADF radio beacons, weather broadcasting
VLF (3–30 kHz)	100 km–10 km	Long-range navigation, sonar
ULF (300–3 kHz)	1 Mm–100 km	Telephone audio range
SLF (30–300 Hz)	6214 mi–621 mi	Communication with submarines, commercial power (60 Hz)
ELF (3–30 Hz)	62 137 mi–6214 mi	Detection of buried metal objects

[a] E = extra, S = super, U = ultra, V = very, H = high, M = medium, L = low, F = frequency.

Broadly speaking, the velocity of propagation of a wave in a nonconductive medium other than free space is determined by the *permittivity* ε and *permeability* μ of the medium. For free space, these are denoted as ε_0 and μ_0 and are given by

$$\begin{aligned} \varepsilon_0 &= \frac{1}{36\pi} \times 10^{-9}\ \frac{\text{F}}{\text{m}} \quad \text{(approximate)} \\ \mu_0 &= 4\pi \times 10^{-7}\ \frac{\text{H}}{\text{m}} \quad \text{(exact)} \end{aligned}$$

The units of ε are farads per meter or a capacitance per distance. The units of μ are henrys per meter or an inductance per distance. We will see these combinations of units several times in later portions of this text and in different contexts. The velocity of propagation in free space (air) is given in terms of these as

$$\begin{aligned} v_0 &= \frac{1}{\sqrt{\varepsilon_0 \mu_0}}\ \frac{\text{m}}{\text{s}} \\ &= 3 \times 10^8\ \frac{\text{m}}{\text{s}} \quad \text{(approximate)} \end{aligned} \tag{1.10}$$

Other media through which the wave may propagate are characterized in terms of their permittivity and permeability *relative to that of free space*, ε_r and μ_r, so that $\varepsilon = \varepsilon_r \varepsilon_0$ and $\mu = \mu_r \mu_0$. For example, Teflon has $\varepsilon_r = 2.1$ and $\mu_r = 1.0$. Note that the permeability μ is the same as in free space. This is an important property of *nonferrous or nonmagnetic* materials. On the other hand, the permeability of sheet steel (a ferrous or magnetic material) is 2000 times that of free space, $\mu_r = 2000$, whereas it has a relative permittivity of $\varepsilon_r = 1.0$. Be aware that permeability is affected by the strength of the applied magnetic field and the frequency of that field, and in general decreases rapidly for most materials from the dc value most often quoted in the literature.

For nonconductive media, other than free space, the velocity of wave propagation is

$$\begin{aligned} v &= \frac{1}{\sqrt{\varepsilon \mu}} \\ &= \frac{v_0}{\sqrt{\varepsilon_r \mu_r}} \end{aligned} \tag{1.11}$$

For example, a wave propagating in Teflon ($\varepsilon_r = 2.1$, $\mu_r = 1$) has a velocity of propagation of

$$\begin{aligned} v &= \frac{v_0}{\sqrt{\varepsilon_r \mu_r}} \\ &= \frac{3 \times 10^8\ (\text{m/s})}{\sqrt{2.1 \times 1}} \\ &= 207{,}019{,}667.8\ \frac{\text{m}}{\text{s}} \\ &= 0.69\ v_0 \end{aligned}$$

Dielectric materials ($\mu_r = 1$) have relative permittivities (ε_r) typically between 2 and 12, so that velocities of propagation range from 0.7 v_0 to 0.29 v_0 in dielectrics. Table 1.3 gives ε_r for various dielectric materials. Table 1.4 gives the relative permeability and relative conductivity (relative to Copper) for various metals.