Introduction to Electromagnetic Compatibility

Second Edition

CLAYTON R. PAUL
Department of Electrical and Computer Engineering, School of Engineering, Mercer University, Macon, Georgia and Emeritus Professor of Electrical Engineering, University of Kentucky, Lexington, Kentucky

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This textbook is dedicated to
The humane and compassionate treatment of animals

"For every difficult problem there is always a simple answer and most of them are wrong."

"When you can measure what you are speaking about and express it in numbers you know something about it; but when you cannot measure it, when you cannot express it in numbers your knowledge is of meagre and unsatisfactory kind; it may be the beginning of knowledge but you have scarcely progressed in your thoughts to the stage of science whatever the matter may be."

Lord Kelvin

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Preface

This is the second edition of a textbook that was originally published in 1992 and is intended for a university/college course in electromagnetic compatibility (EMC). It has also proved to be very beneficial as a reference for industrial professionals interested in EMC design. The prerequisites are the completion of the basic undergraduate electrical engineering courses in electric circuit analysis, signals and systems, electronics, and electromagnetic fields. The text builds on those basic skills, principles, and concepts and applies them to the design of modern electronic systems so that these systems will operate compatibly with other electronic systems and also comply with various governmental regulations on radiated and conducted electromagnetic emissions. In essence, EMC deals with *interference* and the prevention of it through the design of electronic systems.

The subject of EMC is rapidly becoming as important a subdiscipline of electrical engineering (EE) as other more traditional subjects such as electric circuit analysis and electronics. One of the first such courses in EMC that was introduced into an EE undergraduate curriculum was organized in the early 1980s at the University of Kentucky by the author. It was taught as a senior technical elective and continues to be taught as an elective course there and at the author's present institution, Mercer University. The subject is rapidly increasing in importance, due in part to the increasing use and speeds of digital electronics in today's modern world. It is currently being offered in a large number of electrical engineering curricula in schools in the United States and throughout the world. The number of schools offering an EMC course will no doubt continue to rapidly increase. The reasons for EMC having grown in importance at such a rapid pace are due to (1) the increasing speeds and use of digital electronics in today's world and (2) the virtual worldwide imposition of governmental limits on the radiated and conducted noise emissions of digital electronic products. Prior to 1979, the United States did not restrict the electromagnetic noise emissions of digital electronic products that were to be sold within its borders. Manufacturers of digital electronic devices voluntarily imposed their own limits in order to produce quality products whose electromagnetic emissions would not cause interference with other electronic devices. In addition, manufacturers tested their products to determine their susceptibility to electromagnetic emissions from other sources so that the product would operate reliably in the intended environment. In 1979 the U.S. Federal Communications Commission (FCC) published a law that placed legal limits on the radiated emissions from and the conducted emissions out the device power cord of all *digital devices* (devices that use a clock of 9 kHz or greater and use "digital techniques") to be sold in the United States. This transformed what was a voluntary matter into a legal one. This made it illegal to sell a digital device (no matter how innovative the device) in the United States unless its noise emissions were below the limits set by the FCC. Many countries throughout the world, and primarily those of Europe, already had similar such laws in place. This caused a drastic change in how companies producing electronic products design those products. It no longer mattered that the product had some new and revolutionary use or function; if it did not comply with these legal limits, it could not be placed on the market!

Since the original publication of this text in 1992, several significant developments occurred that have dramatically increased the importance of EMC in not only universities but also across the electronics industry. Countries in Europe (which represents a major market for electronics produced in the USA) formed the European Union and imposed even more stringent and pervasive EMC regulations than were in place before the turn of the century. Processing speeds (clock and data speeds) of digital products have increased at a dramatic rate. In the mid 1980s the clock speeds were on the order of tens of megahertz (MHz). Personal computers are now available with clock frequencies over 3 GHz and that cost under $500 U.S. This has dramatically increased the difficulty of complying with the EMC governmental regulations. The combination of lowered costs and higher speeds of digital devices mean that effective EMC design practices are now much more critical in order to avoid unnecessary costs of EMC suppression measures that are added to bring the products into compliance. Frequencies of use even in analog systems are escalating well into the GHz range, and it is difficult to find a product (including washing machines, automobiles, etc.) that doesn't use digital electronics as a primary factor in that product's performance. These mandatory governmental requirements to minimize a digital product's electromagnetic noise emissions and the rapidly decreasing costs and product development schedules of those products mean that all EEs must now be trained in proper EMC design techniques. Electrical engineers that have not been trained in EMC design will be severely handicapped when they enter the workplace.

This second edition has been substantially rewritten and revised to reflect the developments in the field of EMC. Chapters have been repositioned and their content revised. Chapter 1, Introduction to Electromagnetic Compatibility (EMC), has remained essentially the same as in the first edition. An important discussion of the concept of an *electromagnetic wave* has been added to that chapter. Chapter 2, EMC Requirements for Electronic Systems, although retaining its previous place in the outline, has been substantially revised to reflect the rather substantial revisions of the governmental regulatory requirements that have occurred in the

United States and throughout the world. Chapter 3, Signal Spectra—the Relationship between the Time Domain and the Frequency Domain, was moved from its previous place as Chapter 7 in the first edition to its present place as Chapter 3. This was done because the author feels that this topic is one of the—if not the—most important topic in EMC, and this repositioning is intended to get the reader to begin thinking in terms of signal spectra early on. Use of SPICE (simulation program with integrated circuit emphasis) [PSPICE (personal computer SPICE)] in computing signal spectra has now been included in that chapter. Chapter 4, Transmission Lines and Signal Integrity, has been significantly revised. A significant revision of this chapter is the inclusion of the topic of signal integrity. Some 10 years ago when this text was originally published, clock and data speeds were in the low MHz range and hence land lengths on printed circuit boards (PCBs) were inconsequential; their electromagnetic effects could generally be ignored. The propagation delays through the gates were on the order of tens of nanoseconds and dominated the delay caused by the signal lands. Now, virtually all lands on PCBs must be treated as transmission lines, or else the product will not function properly. This is a result of the length of the PCB traces becoming significant portions of a wavelength because of the dramatic increase in the spectral content of the digital signals. Matching of these *transmission lines* is now not an option. Again, use of SPICE (PSPICE) in the analysis of these interconnect leads has been given greater emphasis in this chapter. Chapter 5, Nonideal Behavior of Components, has been moved earlier from its place as Chapter 6 in the previous edition and is retained as a part of the early discussion of important concepts. It has been revised but contains substantially the same content and topic areas.

Chapter 6, Conducted Emissions and Susceptibility, is essentially the same as Chapter 7 of the first edition. In this second edition it appears before the topic of radiated emissions to reflect the author's feeling of its proper sequence. Chapter 7, Antennas, is essentially the same as Chapter 5 in the first edition. Chapter 8, Radiated Emissions and Susceptibility, is essentially the same as Chapter 8 of the first edition but has been revised. Chapter 9, Crosstalk, has been substantially revised from its version as Chapter 10 of the first edition. The mathematics has been considerably simplified. There are three significant revisions in this chapter. First, the simple inductive–capacitive coupling model for weakly coupled, electrically short lines has been moved earlier in the chapter, and its derivation now is argued on somewhat intuitive grounds to simplify the discussion. Second, the computation of the per-unit-length parameters is shown using static numerical methods (method of moments) in a simple fashion in order to familiarize the reader with the modern numerical methods that are growing in use and importance. FORTRAN programs are described here and in Appendix C that compute these parameters very accurately for ribbon cables, PCB land structures, coupled microstrip lines, and coupled striplines. These FORTRAN codes are contained in a CD that is supplied with this textbook. Third, a FORTRAN program that prepares an exact SPICE (PSPICE) subcircuit model for a coupled transmission line is described, and its use is illustrated throughout the chapter. It is also supplied on that CD. The importance of this is that the reader can now easily investigate crosstalk on complicated (but realistic) transmission lines on PCBs that have realistic loads such as capacitors, inductors, transistors, and logic gates, which complicate a hand analysis. This also introduces the reader to the modern use of computer-aided design (CAD) simulation methods that are increasing in importance and popularity. Chapter 10, Shielding, is essentially the same as Chapter 11 of the first edition. Chapter 12 on electrostatic discharge in the first edition has been eliminated as a separate chapter in the second edition, but its content has been incorporated into the final chapter, Chapter 11, System Design for EMC (which was the previous Chapter 13 of the first edition).

The text of that chapter has been virtually rewritten in both content and organization from its earlier version. It is now organized into five major topic areas: Section 11.1, Changing the Way We Think about Electrical Phenomena; Section 11.2, What Do We Mean by the Term “Ground”?; Section 11.3, Printed Circuit Board (PCB) Design; Section 11.4, System Configuration and Design; and Section 11.5, Diagnostic Tools. This was done to cause the reader to focus on the important aspects of EMC design without getting lost in detail. Section 11.5, Diagnostic Tools, is new to the text and reflects the author’s view that it is virtually impossible to design a digital device to pass the regulatory requirements on the first testing. It is crucially important in this age of low product cost and reduced development schedules to be able to determine the exact cause of the noncompliance and to determine how to bring the product into compliance with minimum added cost and minimum impact on the development schedule. The important concept of Dominant Effect is critical to the rapid diagnosis of EMC problems and the demystifying of EMC and is discussed here.

Several appendixes are new to this second edition. Appendix A, The Phasor Solution Method, is a brief review of the important phasor solution of differential equations and electric circuits: their sinusoidal, steady-state solution. This skill is the most important and fundamental skill of an electrical engineer. It permeates all electrical engineering areas, such as circuit analysis, signal analysis, system analysis, electronic circuit analysis, and electromagnetics. Unless the reader has this important skill mastered, very little can be gained or understood from this textbook or any other electrical engineering textbook. Hence this appendix serves as a brief review of this crucial skill. Appendix B, The Electromagnetic Field Equations and Waves, is a brief but sufficient review of the important electromagnetic principles and laws. It was placed in an appendix rather than in the body of the text, as in the first edition, in order to avoid breaks in the flow of the material. Appendix C, Computer Codes for Calculating the Per-Unit-Length Parameters and Crosstalk of Multiconductor Transmission Lines, describes the FORTRAN programs that can be used to model and predict crosstalk of complex (but representative) transmission lines. These are also placed on the CD that is supplied with this textbook. Appendix D, A SPICE (PSPICE) Tutorial, is a brief but sufficient tutorial on the use of the PSPICE program to model and simulate electric circuits.

This edition of the textbook has emphasized a dramatic increase in the use of PSPICE to simulate virtually all areas of EMC analysis. Again, this is in line with the current emphasis on and use of modern CAD tools in EMC. Another significant innovation in this text is the use of worked-out Example Problems and Review Exercises. Detailed worked-out examples are strategically placed after discussion of major concepts to show the reader how to work important EMC problems. These are clearly delineated from the text to enable the reader to focus on these problem-solving skills. In addition, a large number of Review Exercises are included after discussion of each important topic. The exercises are in the form of a simple question, and the answer is given. Hence the reader can quickly check his/her comprehension of the topic immediately after its discussion. Most of the End-of-Chapter Problems are new and the answers are given at the end of the problem in brackets [ ], as was the custom in the first edition.

The Author would like to thank Cadence Design Systems, Inc. for allowing John Wiley Interscience to distribute OrCAD and MicroSim software with this book. OrCAD PSPICE version 10 and MicroSim PSPICE version 8 are included in the CD supplied with this textbook. The reader can therefore immediately install the programs on his/her personal computer and begin to perform the simulations in this book.

Many of the author's colleagues in the EMC industry have had considerable influence on his way of thinking about EMC and have contributed significantly to the author's ability to produce this text. Of primary mention are the insights gained from and numerous discussions with Mr. Henry Ott, which have significantly impacted the author's EMC perspective. The author highly recommends Mr. Ott's Website, http://www.hottconsultants.com. It contains links to the latest revisions of the regulations. But more importantly it contains numerous highly detailed and informative tutorial articles and other references on EMC. The author also owes a significant debt of gratitude for this association with and insights gained from working with colleagues in the EMC group at IBM Information Products Division in Lexington, Kentucky (now Lexmark International) during a sabbatical leave in 1984 and consulting there for some 10 years thereafter. Working with those individuals on significant EMC problems was the primary reason why this text was originally published. Primary among those individuals are Mr. Donald R. Bush, Dr. Keith B. Hardin, and Mr. Stephen G. Parker. The late Mr. Donald R. Bush was also a personal friend of the author and had a profound influence on the author, both personally and professionally, for over 30 years. The author would also like to acknowledge and thank Mr. John Fessler of Lexmark International for his discussions on the latest governmental regualtions.

CLAYTON R. PAUL

Macon, Georgia, January 2005

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 also transmit pulses of a single-frequency carrier. As this carrier frequency is pulsed on and off, these pulses radiate outward from the antenna, strike a target, and return to the radar antenna. The total transit time of the wave is directly related to the distance of the target from the radar antenna. The spectral content of this radar pulse 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 with digital computers in particular 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

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frequencies than do slower (longer) transition times. The spectral content of digital devices generally occupies a wide range of frequencies and can also cause 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 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 that is 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 as integral a part of design as, for example, digital design. 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* transfers the emission energy to a *receptor (receiver)*, where it is processed, resulting in either desired or undesired behavior. *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 at the receptor input 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

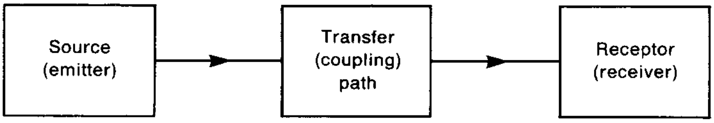

FIGURE 1.1 The basic decomposition of the EMC coupling problem.

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, an AM 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 AM 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 alternatives 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. This is not sufficient reason to use digital signals having 100 ps rise/falltimes when the system will properly function with 1 ns rise/falltimes. Remember that 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. But shielded enclosures are more expensive than reducing the rise/falltime of the emitter, and, more often than not, their actual performance in an installation is 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 will continue to be 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 be unacceptable to the customer.

We may further break the transfer of electromagnetic energy (with regard 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

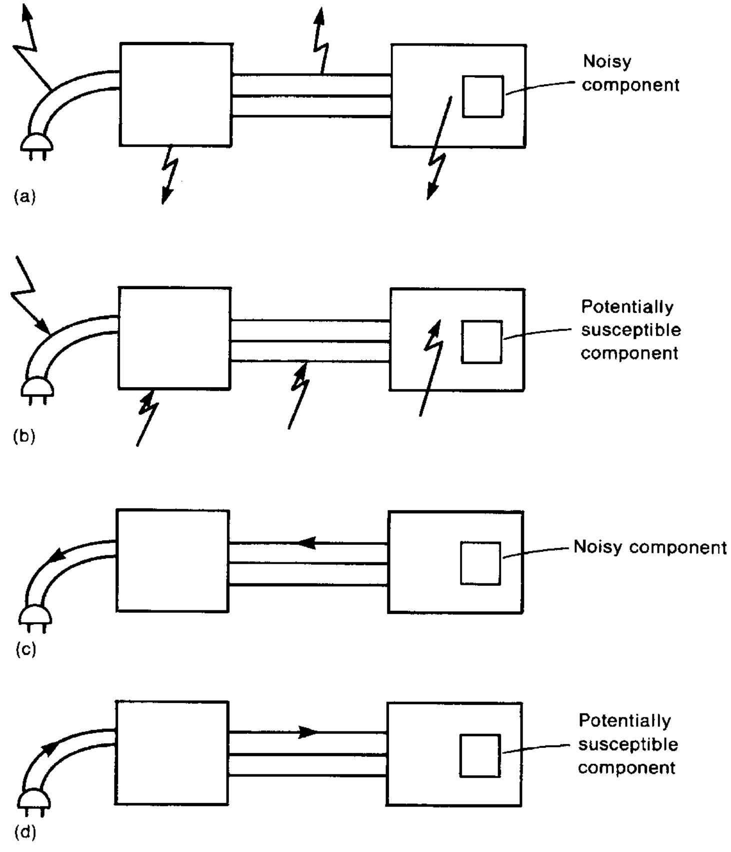

FIGURE 1.2 The four basic EMC subproblems: (a) radiated emissions; (b) radiated susceptibility; (c) conducted emissions; (d) conducted susceptibility.

providing power to these subsystems is usually the commercial ac (alternating-current) power system of the installation site. A power supply in a particular electronic system converts this ac 120 V, 60 Hz voltage (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, 5 V dc is required to power the digital logic, +12 V, and −12 V dc voltages are required to power analog electronics. Other dc voltages are required to power devices such as motors. Sometimes the 60 Hz (50 Hz) ac power is required to power other components such as small cooling fans. The 60 Hz, 120 V 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 of 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 internal signals or external 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, usually plastic. 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, reflect 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 point out that "currents radiate." This is the essential way in which radiated emissions (intentional or unintentional) are produced. A time-varying current is, in effect, accelerated charge. Hence the fundamental process that produces radiated emissions is the acceleration of charge. Throughout the text we will be trying to replace certain misconceptions that prevent an understanding of the problem. An example is the notion that the ac power cord carries only 60-Hz signals. Although the primary intent of this cable is to transfer 60 Hz commercial 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 high-frequency currents appear on this long (1 m or more) cable, they will radiate 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 on this cable as well as any 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