Chapter 1

An Overview of Vacuum Tube Audio Applications

The phrase "high technology" is perhaps one of the more overused descriptions in our technical vocabulary. It is a phrase generally reserved for the discussion of integrated circuits, fiber optics, satellite systems, computers, and handheld portable devices of many varieties. Very few people would associate high technology with vacuum tubes—except audio enthusiasts. Variously described as the "tube sound," amplifiers built around vacuum tubes remain in demand for demanding consumers.

A number of projects are included in this book. Several of those projects—in finished form—are shown in Figure 1.1.

The Evolution of Analog Audio

The use of solid-state technology in all manner of consumer audio devices has made possible the explosion of audio sources and options for consumers—at very attractive prices. It is difficult to imagine a world without personal entertainment devices—although it is sometimes tempting to do so. Whether the personalization of entertainment is a good thing or a not-so-good thing could be debated, probably at some length. It's all academic, of course, since it is here.

Acknowledging up front that this is a book about technology, it is fair to point out that to the end user, audio—perhaps more than any other entertainment medium—is about preferences and real-life experiences. Audio has certain fundamental reference points—loudness, frequency response, noise, distortion, and so forth. It has another dimension as well, and that dimension is perception. With audio, the artist and/or producer has a wide and varied pallet with which to paint. There are few absolutes when it comes to audio perception. With video, on the other hand, absolutes abound. Viewers know that the grass should be green and the sky should be blue and people should look like … people. Audio has the capacity for texture and subtlety, which frankly makes it more interesting.

FIGURE 1.1 Some of the vacuum tube audio amplifier projects detailed in this book—in finished form.

Audio is, of course, more than music. However, music makes up a large part of what we consider audio and what consumers use the technologies of audio for. The social impact of audio (music) should not be underestimated. Music provides reference points for our lives. Most everybody can relate to hearing a song play and reflecting back to a particular event in their life—sometimes from the very distant past. This social aspect was probably more profound in the era of the 1950s through the 1970s when most listening to music was a group event focusing on a limited number of radio stations. When a new album was released by a given performer, most everyone in a particular age group heard it and reacted to it. For better or worse, this gave generations of listeners various reference points to which they can still relate. The revolution in personal entertainment devices has, to a large degree, diluted this group experience. Whether this is important to anybody remains to be seen.

It is easy to argue that consumer audio has been in a long march toward the lowest common denominator, focused on cost and size more than performance. Others may wish to debate that, but regardless, the manufacturers in this space have been giving consumers what they want. And it's hard to argue with that. Still, for consumers who are looking for more than just convenience from their audio system, options are—thankfully—still readily available.

The author, like some percentage of readers of this book (perhaps a large percentage), grew up in the 1960s. With an interest in electronics, that meant also an interest in vacuum tubes. By 1970, consumer electronics manufacturers had moved in large measure to transistorized amplifiers, tuners, portable radios, and so on. Intrigued by this new technology, few of us realized what we were giving up by discarding vacuum tube equipment in favor of new solid-state hardware. But because personal storage space is never unlimited, the old stuff went away in favor of new stuff (which went away later). If you are reading this book (and there is a good chance that you are), you, like the author, have rediscovered what we all thought was out of date three or four decades ago.

The author can remember in the early 1970s literally running away from vacuum tube circuits to embrace transistor-based circuits. Transistors were—of course—better, smaller, cheaper, newer. And, most importantly, solid-state circuits always provided improved performance over their tube counterparts. Or so we all thought (or at least a lot of us thought). Looking back now with the benefit of history, it is clear that solid-state devices did some things very well and tubes did other things very well. Today, there is room for both in any entertainment center.

In preparation for this book, the author began collecting various types of vintage tube hardware from eBay and other sources with the intent of refurbishing it. These projects served as a reminder that: 1) this stuff is fun to work with; 2) circuits based on vacuum tubes are interesting; 3) circuits based on vacuum tubes are understandable (in contrast to many products today, which are really understood by only a very small number of people); and 4) vacuum tubes are actually quite reliable. The last point deserves some elaboration. The author, in his refurbishing projects, has found (to some surprise) that a lot of hardware built 50 years ago will actually still light up and do something useful (if the old electrolytics do not smoke first). The surprising find was that tubes, when properly cared for, actually *were* reliable. And they still are.

Technology Waves

It is useful to review the progression of consumer audio devices over the past few decades. They have tended to come in a series of waves. Various benchmarks or inflection points for consumer audio technologies can be identified; however, as a first-order approximation, the following general divisions seem to cover most of the bases.

Pre-1950

Characterized by physically large systems with limited features, pre-1950s audio equipment was usually nothing to write home about—or remember for that matter. These sets were, by and large, big pieces of furniture designed for one or two functions—radio and/or records. One bright spot in the stock receiver, however, was the typical frequency response of the AM radio circuits. During the 1950s as the number of AM radio stations grew rapidly, set designers had to adjust their filtering schemes to accommodate additional interference from nearby (and at night distant) stations. One common approach was to limit the bandwidth of the received signal. This limited interference, but, of course, also limited frequency response. The growth of AM radio was a classic case where success was not necessarily a good thing, at least from the standpoint of sonic performance. The pre-1950s receivers were invariably intended for fixed operation, some with the capability to add an external long-wire antenna for reception of shortwave broadcasts.

1950s Audio

The evolution in consumer electronics continued with improved receivers (frequency response notwithstanding) and higher-quality turntables. While the "45" record came on strong in the 1950s, the LP had also firmly established itself as the medium for high-fidelity listening at home. The large furniture-piece sets began to give way to smaller single-function devices. The extra space in the living room was, of course, quickly consumed by television receivers. (We won't discuss their audio performance here.) Portable radios also appeared, using tubes at first, and powered by large dry-cell batteries (not rechargeable). Radios also started appearing in automobiles in large numbers, typically using innovative (if not elegant) methods of generating the necessary operating voltages for tubes from a 12 V DC power source (enter the "vibrator" device that chopped the direct-current source to simulate an alternating-current source, which was applied to a step-up transformer).

High-end audio equipment began appearing, marketed to an emerging discriminating audience. Some of these systems were very good—very, very good. With 3 dB frequency response points of less than 10 Hz and greater than 100 kHz, these amplifiers set the pace for high-fidelity systems that followed. This development is even more impressive when considering that virtually no source material existed that would fully take advantage of the capabilities of the amplifier—certainly not AM radio or even the developing FM radio, and certainly not the vinyl records then available.

1960s Audio

Behold the transistor radio. Small enough to fit in a shirt pocket, the capabilities of this miniature marvel were often described in terms of the number of transistors used. One would assume that a seven-transistor radio was better than a five-transistor radio. With their two-inch speakers, it was hard to tell the difference anyway. But, this new device gave consumers portability, and they liked it. Despite the inroads made by transistors, vacuum tubes still reigned supreme. Audio systems with high-quality turntables as the input source moved into mainstream use and ushered in a (here it comes) "golden era" of audio.

On the receiver side, reduction in size seemed to be the main trend, exemplified by the five-tube table-top AM radio shown in schematic form in Figure 1.2. The high-end models included a clock and "wake to music" alarm. FM receivers began to appear in large numbers, driven by the high-quality audio (and even stereo) programming available. The growing number of counterculture rock music stations didn't hurt either.

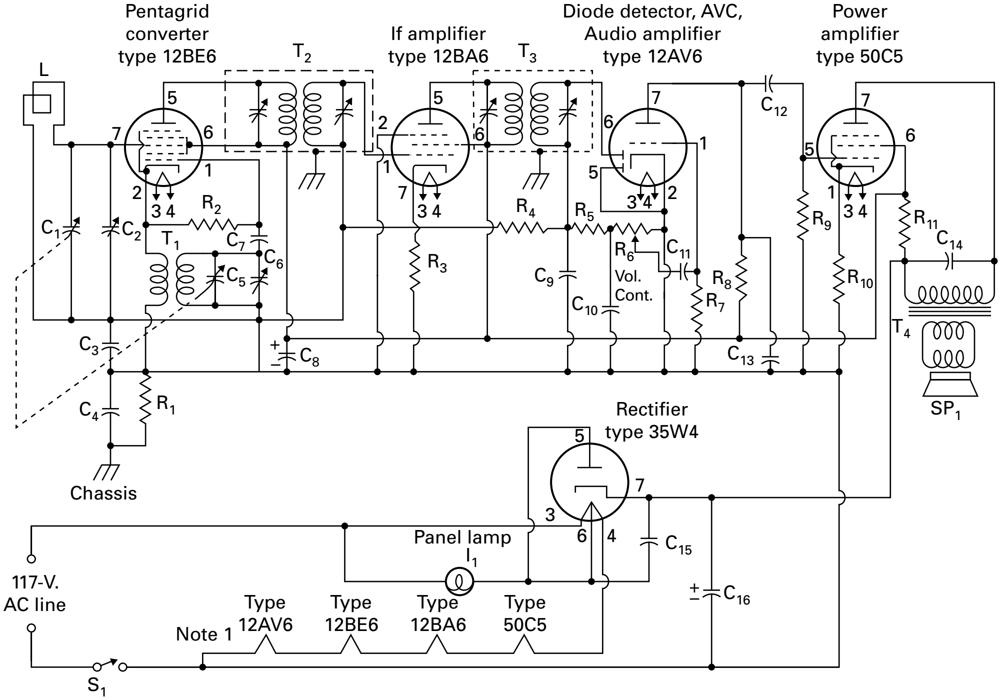


FIGURE 1.2 Schematic diagram of the classic five-tube table-top AM radio. (*From* [1].)

Reel-to-reel tape recorders also appeared at reasonable prices for consumers, with a limited selection of music available on reels of various sizes. Readers will recall the three common speeds (1-7/8, 3-3/4, and 7-1/2 inches per second) and the various reel sizes (3-1/2, 5, and 7 inches for consumer products).

Console Audio

The furniture radio set of 1950 came back in the 1960s as an entertainment center that included, depending on the model, an AM receiver, FM receiver, turntable, and perhaps television set. One could argue this was the last stand for audio furniture in the home. While the focus of these systems seemed to be mostly features and convenience rather than overall performance, they were the focal point of countless living rooms for many years. They also served to advance the concept of high-quality audio entertainment for consumers who were enamored with the shirt-pocket transistorized AM radio but recognized that some things are worth sitting down to listen to.

Component Audio

The 1970s were all about component audio. Designers took the console audio systems of the 1960s and broke them into discrete devices, reasoning they could enhance the performance and features in the process. They were right on both counts. Consumers loved them. The component audio system continued to evolve and reach a high level of sophistication and sonic performance. Systems could be found built using vacuum tubes, solid-state devices, or both. Some of the most innovative and memorable audio systems ever built were built in this era.

The genius of component audio was that it allowed consumers to build a system over time into exactly what they wanted it to be. Component audio systems also offered considerable flexibility in that units could be mixed and matched to yield just the system envisioned by the consumer. The interface/connector problems that bedevil consumers today were not really an issue in the 1970s and 1980s, as nearly every input and output (other than the speakers) used the trusty RCA connector. Couple this simplicity with look-alike styling that produced an attractive tower of audio and happy consumers were guaranteed.

Back to the Present

Component audio systems were the mainstay of consumer audio for decades—and for good reason. But like every trend in home appliances, the component system has been challenged by other approaches to consumer audio—most notably the personal audio player and the wide variety of accessory devices that have clustered around the player to embellish, extend, and otherwise enhance it. At the other extreme, the component architecture has been challenged by home server systems that harness the capabilities of computers and wired/wireless networks to store huge amounts of content and move it more or less seamlessly around the house to be consumed privately or collectively.

Along with the move toward personal audio (and video) players has come the notion that small is good—at least as it relates to audio entertainment devices. (The size of flatscreen video displays is another matter entirely—limited only by wall size and available funds.) The bookshelf (or even floor-standing) speakers that dominated living spaces in the 1980s and 1990s have been replaced in many homes by small speakers utilizing a common subwoofer. For a number of consumers, the performance is good enough and the prices are certainly attractive.

Having acknowledged there are trends, of course, does not mean everyone needs to follow them.

Tube vs. Solid State

The corner piece of the component audio system is—inevitably—the power amplifier. As transistors replaced tubes and integrated circuits replaced transistors and surface-mounted devices replaced integrated circuits, the measurable performance of audio systems has steadily improved, sometimes dramatically so. The benefits of solid-state technologies in low-level audio circuits are well known, beginning with noise and distortion performance. Similar attributes apply to radio frequency (RF) circuits. In the case of disc players (CD and DVD) it's all about data, and what we generally consider audio plays a relatively minor role at the end of a long chain of logic gates.

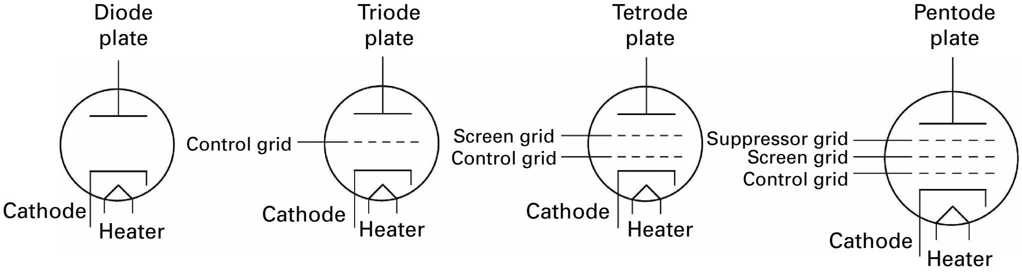


FIGURE 1.3 The primary types of vacuum tubes. Variations also exist where combinations of these basic elements are enclosed within the glass envelope.

As for the power amplifier, however, the choice between solid-state and vacuum tubes is not so clear-cut.

While it is certainly true that solid-state preamplifiers (preamp) and power amplifiers solved a host of shortcomings of their predecessor vacuum tube amplifiers, a certain sonic quality was lost in the process. Often described in nonscientific terms, the “warmth” of the tube sound nonetheless exists and has attracted a loyal following. Vacuum tube–based audio equipment remains in demand and is likely to remain so for a long time.

Various explanations have been offered over the years to define the tube sound and how it differs from audio produced using solid-state devices. This comparison is made more difficult by the differing amplifier architectures that have been used to construct transistor-based power amplifiers in order to improve efficiency and/or measured performance. It is arguable, however, that identifying the characteristics that define the differences is not really all that important. It is probably sufficient to simply acknowledge that there are differences and accept them. As noted earlier in this chapter, audio is all about how humans react to it. How a selection of music is heard (perceived) is—in the end—more important than the documented transfer characteristics of the active devices contained in the amplifier.

Viewed objectively, it is evident that some very good vacuum tube amplifiers were offered to consumers, and some very bad ones were offered as well. The tradeoff between price point and performance is neither new nor limited to electronic devices. By the same token, there have been some very good solid-state amplifiers offered to consumers, and some very bad ones too.

Vacuum tubes (known in earlier times as “receiving tubes” or alternately as “valves”) include a wide range of devices, each for a specific class of applications. Devices include diodes, triodes, tetrodes, and pentodes, as illustrated in Figure 1.3. These devices hold an important position in high-fidelity audio.

Engineering Tradeoffs

Designing a consumer product is almost always an exercise in tradeoffs. The variables include (but are certainly not limited to) complexity, component count, bill of materials, feature set, manufacturability, power requirements, cooling requirements, and time-to-market. A "perfect" audio device would likely be a commercial flop because it cost too much, consumed too much power, generated too much heat, and was never finished. Well, that may be a bit of an exaggeration, but perhaps not by much.

Design tradeoffs are a part of engineering. The first step in the design of any product is to clearly define what that product is supposed to do. The second step is to understand what the consumer wants from the product and how much they are willing to pay for it. Other engineering decisions branch out from there.

Basic System Choices

Focusing on vacuum tube audio amplifiers in general, and this book in particular, before setting out to build an amplifier, it is necessary to answer some basic questions:

- *What is the intended application?* Options include: 1) turntable preamp, 2) microphone preamp, 3) line-level preamp, 4) equalizer (tone control) preamp, or 5) power amplifier (and, of course, a power supply needed to make options 1–5 work). As a practical matter, any system will likely include some combination of these functions, and perhaps other functions as well. For the purpose of this book we will plan on all six functions listed here.
- *What are the desired active devices?* Options include: 1) solid-state, 2) vacuum tube, or 3) a combination of each. For a consumer product, this choice is fundamental and driven by many factors—some technical, some not. For the purpose of this book, however, it is clear the desired active devices will be vacuum tubes or a combination of tubes and solid-state devices. For a power amplifier, the required output level is a fundamental consideration that determines the overall architecture of the system (e.g., single-ended, push-pull, parallel, etc.).
- *What is the intended form factor?* Options include: 1) stand-alone device, 2) component system, 3) integrated with another device (such as a turntable or speaker), or 4) something else. The form factor dictates a major cost of the project—namely, the physical enclosure (case). For this book we will assume a component system built using off-the-shelf sheet metal components with limited custom cutting as needed.
- *What is the preferred construction method?* Options include: 1) printed wiring board (PWB), 2) hand-wired, or 3) a combination of both techniques. Any of the three approaches are practical for vacuum tube designs. While the PWB method results in simpler construction (once the PWB has been designed and produced) and a neater appearance, the heat generated by vacuum tubes must be considered. As such, a hybrid approach where the tubes are mounted on the metal chassis and tied by interconnecting wires to the PWB may be preferred. A completely hand-wired chassis is also an option—perhaps the sentimental favorite given the history of the vacuum tube. For experimentation or a one-off project, it's hard to beat a hand-wired chassis for low cost, simplicity, and long-term performance.
- *Will the design be limited to off-the-shelf components?* In an effort to extract the last measure of performance from a tube amplifier, some audiophiles choose to build custom components, such as winding the output transformer to certain

specifications. While the benefits of this approach can be significant for the experienced builder, for the purpose of this book the scope of the projects will be limited to off-the-shelf components. This approach makes certain assumptions about the level of detail that most readers are interested in for most projects most of the time.

- *What is the maximum estimated cost for the finished unit*? With any project or product, it is rare to encounter a situation where money is not a consideration. For the purpose of this book, unlimited funds will not be assumed. It is also important to point out that the estimated cost for most any project is often exceeded well before the project has been completed.
- *How much time is available to build the unit*? Like unlimited funds, unlimited time is usually in short supply as well. For this book it is assumed that while building an audio amplifier should be an enjoyable project, it should not consume the builder's life.
- *Do I have the technical ability to do this*? Yes, of course you do!

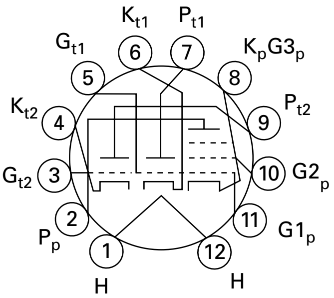
Continuing Development of Vacuum Tubes

In the realm of vacuum tubes, there is a natural division between two fundamental classes of devices: receiving tubes and power tubes. Power vacuum tubes cover a wide range of devices, many exotic, and are still used in countless applications. Due to improvements in solid-state devices, power vacuum tube development has focused on high powers and high frequencies where their unique advantages can be exploited. The power levels possible with vacuum devices are truly astounding—many hundreds of kilowatts power output from a single device is not uncommon at ultra-high frequencies (UHF). No solid-state device can match this level of performance. This being the case, tube development continues as engineers push the limits of power output, maximum operating frequency, efficiency, and reliability.

The primary frontier in power vacuum tube development today is materials technology. New and improved devices depend on new and improved materials. This is an exciting area of applied science where evolutionary progress continues to be made.

Receiving tubes do not enjoy the same developmental effort on new devices, but producers are still exploring ways of improving classic models and optimizing production techniques. The continued demand for receiving tubes drives this work. Numerous retail sources exist for receiving tubes, both new and vintage stock.

Apart from continuing refinements in manufacturing methods, the last major technology advancement for the receiving tube was probably the "integrated vacuum tube." This class of device, known by various trade names (e.g., "Compactron"), took the elements of various basic tube types and combined them to form a larger device that performed several functions. One example of this class of device is shown in Figure 1.4.



Legend:
K = cathode for triode (t, 1 or 2) or pentode (p)
P = plate for triode (t, 1 or 2) or pentode (p)
G = grid for triode (t, 1 or 2) or pentode (p)
H = heater

FIGURE 1.4 **Example "integrated vacuum tube" containing two triodes and a pentode within a single glass envelope. This particular device (14BL11) was used in television receiver applications. (*From* [1]).**

Standardization

The need for interchangeability of vacuum tubes in the 1930s and especially the 1940s for military applications drove product standardization and helped make tubes synonymous with electronics. Without a standardized scheme for device labeling, performance, and interconnection, the great advances in electronics made during this period would have been difficult—perhaps impossible.

Product standardization is important for the advancement of any industry—particularly the electronics industry where a large number of individual components is required to construct any single product. Standardization leads to a healthy commercial environment where multiple vendors work to develop new techniques and technologies that advance the science of component design and fabrication. In addition, having multiple vendors for a given device usually results in lower prices to the user.

Nomenclature

If a vacuum tube users group were to sit down and define a numbering/identification system for tubes today, it probably would come up with something quite different from what we actually have. One could imagine a nomenclature that would convey a great deal of information about the device itself. While imperfect, vacuum tube nomenclature is nonetheless stable and predictable, and given the number of devices typically used for audio applications, is quite manageable.

A user can typically assume that the same device type from any of several manufacturers will provide similar nominal performance. As with any product, of course, manufacturers seek to differentiate their offerings from competitors through various attributes, such as higher performance, longer life, and so on. For critical applications it may be necessary to use a particular brand of device to achieve the performance desired. By design, the applications contained in this book will not fall into the "critical performance" category.

It is fair to point out that some users have preferences for particular device brands, and while it may be hard to characterize empirically what those differences are, such preferences are nonetheless valid. Audio, after all, is all about perception of the reproduced sound. Personal preference and past experience can be more significant than any specifications sheet.

Fundamental Electrical Principles Reviewed

Before moving into vacuum tube theory, circuit design, and construction projects, it is worthwhile to review some of the fundamental electrical principles that all readers learned many years ago (perhaps decades ago). A short refresher is probably a good idea.

The Atom

The atomic theory of matter specifies that each of the many chemical elements is composed of unique and identifiable particles called *atoms* [2]. In ancient times only ten were known in their pure, uncombined form; these were carbon, sulfur, copper, antimony, iron, tin, gold, silver, mercury, and lead. Of the several hundred now identified, fewer than 50 are found in an uncombined, or chemically free, form on earth.

Each atom consists of a compact *nucleus* of positively and negatively charged particles (*protons* and *electrons,* respectively). Additional electrons travel in well-defined orbits around the nucleus. The electron orbits are grouped in regions called *shells,* and the number of electrons in each orbit increases with the increase in orbit diameter in accordance with quantum-theory laws of physics. The diameter of the outer orbiting path of electrons in an atom is in the order of one-millionth (10^{-6}) millimeter, and the nucleus, one-millionth of that. These typical figures emphasize the minute size of the atom.

Magnetic Effects

The nucleus and the free electrons of an iron atom are shown in the schematic diagram in Figure 1.5 [2]. Note that the electrons are spinning in different directions. This rotation creates a magnetic field surrounding each electron. If the number of electrons with positive spins is equal to the number with negative spins, then the net field is zero and the atom exhibits no magnetic field.

In the diagram, although the electrons in the first, second, and fourth shells balance each other, in the third shell five electrons have clockwise positive spins, and one a counterclockwise negative spin, which gives the iron atom in this particular electron configuration a cumulative *magnetic effect.*

The parallel alignment of electrons spins over regions, known as *domains,* containing a large number of atoms. When a magnetic material is in a demagnetized state, the direction of magnetization in the domain is in a random order. Magnetization by an external field takes place by a change or displacement in the isolation of the domains, with the result that a large number of the atoms are aligned with their charged electrons in parallel.

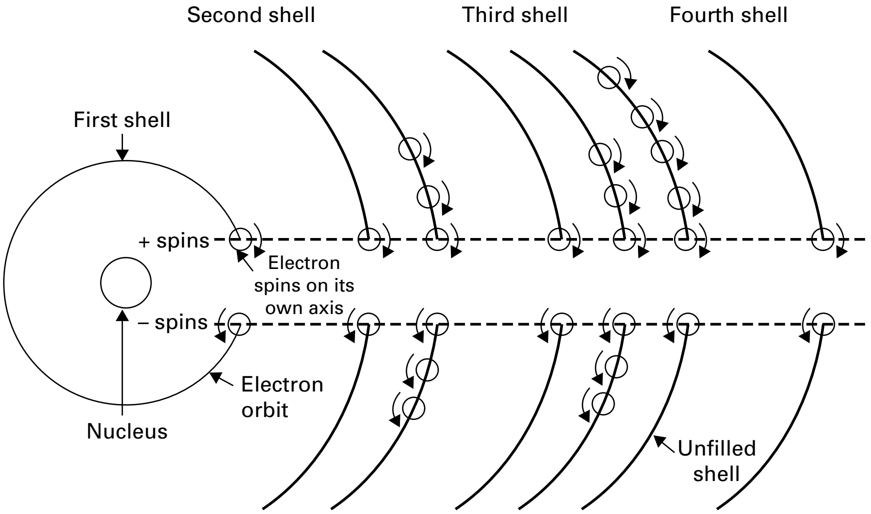


FIGURE 1.5 Schematic of the iron (Fe) atom. (*After* [2].)

Conductors and Insulators

In some elements, such as copper, the electrons in the outer shells of the atom are so weakly bound to the nucleus that they can be released by a small electrical force, or voltage [2]. A voltage applied between two points on a length of a metallic conductor produces the flow of an electric current, and an electric field is established around the conductor. The *conductivity* is a constant for each metal that is unaffected by the current through or the intensity of any external electric field.

In some nonmetallic materials, the free electrons are so tightly bound by forces in the atom that, upon the application of an external voltage, they will not separate from their atom except by an electrical force strong enough to destroy the insulating properties of the material. However, the charges will realign within the structure of their atom. This condition occurs in the insulating material (*dielectric*) of a capacitor when a voltage is applied to the two conductors encasing the dielectric.

Semiconductors are electronic conducting materials wherein the conductivity is dependent primarily upon impurities in the material. In addition to negative mobile charges of electrons, positive mobile charges are present. These positive charges are called *holes* because each exists as an absence of electrons. Holes (+) and electrons (–), because they are oppositely charged, move in opposite directions in an electric field. The conductivity of semiconductors is highly sensitive to, and increases with, temperature.

Direct Current (DC)

Direct current is defined as a unidirectional current in which there are no significant changes in the current flow [2]. In practice, the term frequently is used to identify a voltage source, in which case variations in the load can result in fluctuations in the current but not in the direction.

Direct current was used in the first systems built to distribute electricity for household and industrial power. For safety reasons, and the voltage requirements of lamps and motors, distribution was at the low nominal voltage of 110 V. The losses in distribution circuits at this voltage seriously restricted the length of transmission lines and the size of the areas that could be covered. Consequently, only a relatively small area could be served by a single generating plant. It was not until the development of alternating-current systems and the voltage transformer that it was feasible to transport high levels of power at relatively low current over long distances for subsequent low-voltage distribution to consumers.

Alternating Current (AC)

Alternating current is defined as a current that reverses direction at a periodic rate [2]. The average value of alternating current over a period of one cycle is equal to zero. The effective value of an alternating current in the supply of energy is measured in terms of the *root mean square* (rms) value. The rms is the square root of the square of all the values, positive and negative, during a complete cycle, usually a sine wave. Because rms values cannot be added directly, it is necessary to perform an rms addition as follows:

$$V_{\text{rms total}} = \sqrt{V^2_{\text{rms}1} + V^2_{\text{rms}2} + \ldots V^2_{\text{rms n}} V}$$

As in the definition of direct current, in practice the term frequently is used to identify a voltage source.

The level of a sine-wave alternating current or voltage can be specified by two other methods of measurement in addition to rms. These are *average* and *peak.* A sine-wave signal and the rms and average levels are shown in Figure 1.6. The levels of complex, symmetrical AC signals are specified as the peak level from the axis, as shown in the figure.

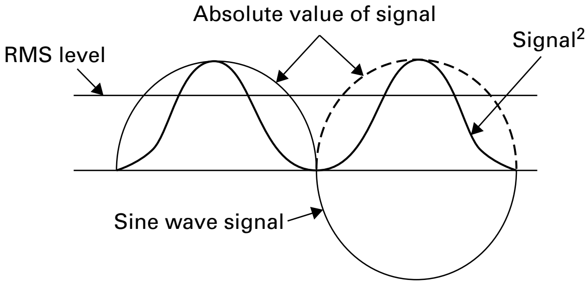


FIGURE 1.6 **Root mean square (rms) measurements. The relationship of rms and average values is shown. (*After* [2].)**

Electronic Circuits

Electronic circuits are composed of elements such as resistors, capacitors, inductors, and voltage and current sources, all of which may be interconnected to permit the flow of electric currents [2]. An *element* is the smallest component into which circuits can be subdivided. The points on a circuit element where they are connected in a circuit are called *terminals.*

Elements can have two or more terminals, as shown in Figure 1.7. The resistor, capacitor, inductor, and diode shown in Figure 1.7*a* are two-terminal elements; the transistor in Figure 1.7*b* is a three-terminal element; and the transformer in Figure 1.7*c* is a four-terminal element.

Circuit elements and components also are classified as to their function in a circuit. An element is considered *passive* if it absorbs energy and *active* if it increases the level of energy in a signal. An element that receives energy from either a passive or active element is called a *load.* In addition, either passive or active elements, or components, can serve as loads.

The basic relationship of current and voltage in a two-terminal circuit where the voltage is constant and there is only one source of voltage is given in Ohm's law. This states that the voltage E between the terminals of a conductor varies in accordance with the current I. The ratio of voltage, current, and resistance R is expressed in Ohm's law:

$$E = I \times R$$

Using Ohm's law, the calculation for power in watts can be developed from $P = E \times I$ as follows:

$$P = \frac{E^2}{R} \text{ and } P = I^2 \times R$$

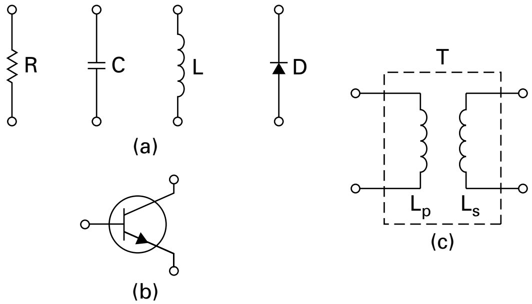


FIGURE 1.7 Schematic examples of circuit elements: (*a*) two-terminal element, (*b*) three-terminal element, (*c*) four-terminal element. (*After* [2].)

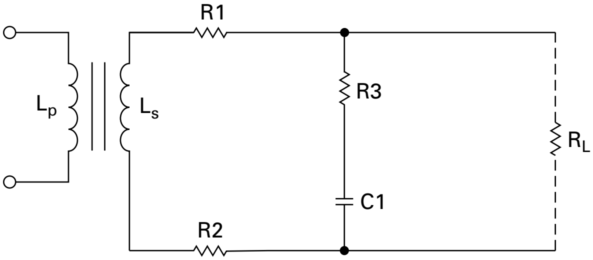


FIGURE 1.8 **Circuit configuration composed of several elements and branches and a closed loop (R1, R3, C1, R2, and L_s). (*After* [2].)**

A circuit, consisting of a number of elements or components, usually amplifies or modifies a signal before delivering it to a load. The terminal to which a signal is applied is an *input port,* or *driving port.* The pair or group of terminals that delivers a signal to a load is the *output port.* An element or portion of a circuit between two terminals is a *branch.* The circuit shown in Figure 1.8 is made up of several elements and branches. R1 is a branch, and R3 and C1 make up a two-element branch. The secondary winding of transformer, a voltage source, and R2 also constitute a branch. The point at which three or more branches join together is a *node.* A series connection of elements or branches, called a *path,* in which the end is connected back to the start, is a *closed loop.*

Circuit Analysis

Relatively complex configurations of linear circuit elements (e.g., where the signal gain or loss is constant over the signal amplitude range) can be analyzed by simplifying them into the equivalent circuits [2]. After restructuring a circuit into an equivalent form, the current and voltage characteristics at various nodes can be calculated using network-analysis theorems, including Kirchhoff's current and voltage laws, Thevenin's theorem, and Norton's theorem.

- **Kirchhoff's current law** (KCL) The algebraic sum of the instantaneous currents entering a node (a common terminal of three or more branches) is zero. In other words, the currents from two branches entering a node add algebraically to the current, leaving the node in a third branch.
- **Kirchhoff's voltage law** (KVL) The algebraic sum of instantaneous voltages around a closed loop is zero.
- **Thevenin's theorem** The behavior of a circuit at its terminals can be simulated by replacement with a voltage E from a DC source in series with an impedance Z (see Figure 1.9*a*).
- **Norton's theorem** The behavior of a circuit at its terminals can be simulated by replacement with a DC source I in parallel with an impedance Z (see Figure 1.9*b*).

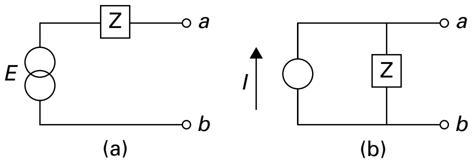


FIGURE 1.9 Equivalent circuits: (*a*) Thevenin's equivalent voltage source, (*b*) Norton's equivalent current source. (*After* [3].)

Static Electricity

The phenomenon of static electricity and related potential differences concerns configurations of conductors and insulators where no current flows and all electrical forces are unchanging; hence the term *static* [2]. Nevertheless, static forces are present because of the number of excess electrons or protons in an object. A static charge can be induced by applying voltage to an object. A flow of current to or from the object can result from either a breakdown of the surrounding nonconducting material or by the connection of a conductor to the object.

Two basic laws regarding electrons and protons are

- Like charges exert a repelling force on each other; electrons repel other electrons and protons repel other protons.
- Opposite charges attract each other; electrons and protons are attracted to each other.

Therefore, if two objects each contain exactly as many electrons as protons in each atom, there is no electrostatic force between the two. On the other hand, if one object is charged with an excess of protons (deficiency of electrons) and the other an excess of electrons, there will be a relatively weak attraction that diminishes rapidly with distance. An attraction also will occur between a neutral and a charged object.

Another fundamental law governing static electricity, developed by Faraday, is that all of the charge of any conductor not carrying a current lies in the surface of the conductor. Thus, any electric fields external to a completely enclosed metal box will not penetrate beyond the surface. Conversely, fields within the box will not exert any force on objects outside the box. The box need not be a solid surface; a conduction cage or grid will suffice. This type of isolation frequently is referred to as a *Faraday shield.*

Magnetism

The elemental magnetic particle is the spinning electron [2]. In magnetic materials, such as iron, cobalt, and nickel, the electrons in the third shell of the atom are the source of magnetic properties. If the spins are arranged in parallel, the atom and its associated domains or clusters of the material will exhibit a magnetic field. The magnetic field of a magnetized bar has lines of magnetic force that extend between the ends, one called the north pole and the other the south pole, as shown in Figure 1.10*a*. The lines of force of a magnetic field are called *magnetic flux* lines.

Electromagnetism

A current flowing in a conductor produces a magnetic field surrounding the wire as shown in Figure 1.11*a* [2]. In a coil or solenoid, the direction of the magnetic field relative to the electron flow (– to +) is shown in Figure 1.11*b*. The attraction and repulsion between two iron-core electromagnetic solenoids driven by direct currents is similar to that of two permanent magnets described previously.

The process of magnetizing and demagnetizing an iron-core solenoid using a current applied to a surrounding coil can be shown graphically as a plot of the magnetizing field strength and the resultant magnetization of the material, called a *hysteresis loop* (Figure 1.12). At the point where the field is reduced to zero, a small amount of magnetization, called *remnance,* remains.

Magnetic Shielding

In effect, the shielding of components and circuits from magnetic fields is accomplished by introducing a magnetic short circuit in the path between the field source and the area to be protected [2]. The flux from a field can be redirected to flow in a partition or shield of magnetic material, rather than in the normal distribution pattern between north and south poles. The effectiveness of shielding depends primarily upon the thickness of the shield, the material, and the strength of the interfering field.

Some alloys are more effective than iron. However, many are less effective at high flux levels. Two or more layers of shielding, insulated to prevent circulating currents from magnetization of the shielding, may be used in low-level audio, video, and data applications.

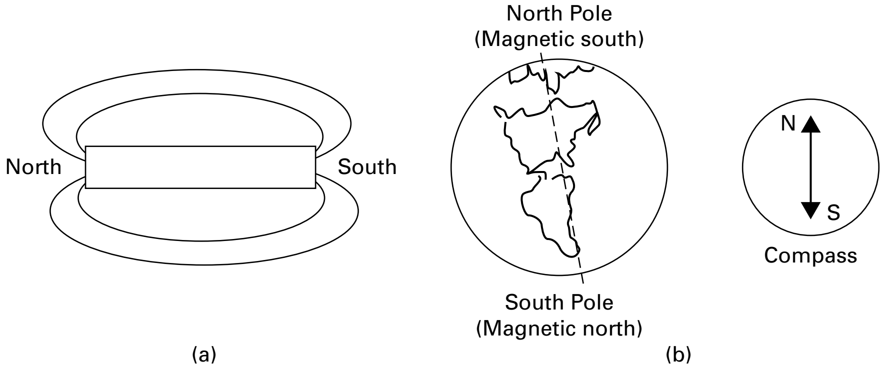


FIGURE 1.10 The properties of magnetism: (*a*) lines of force surrounding a bar magnet, (*b*) relation of compass poles to the earth's magnetic field. (*After* [2].)

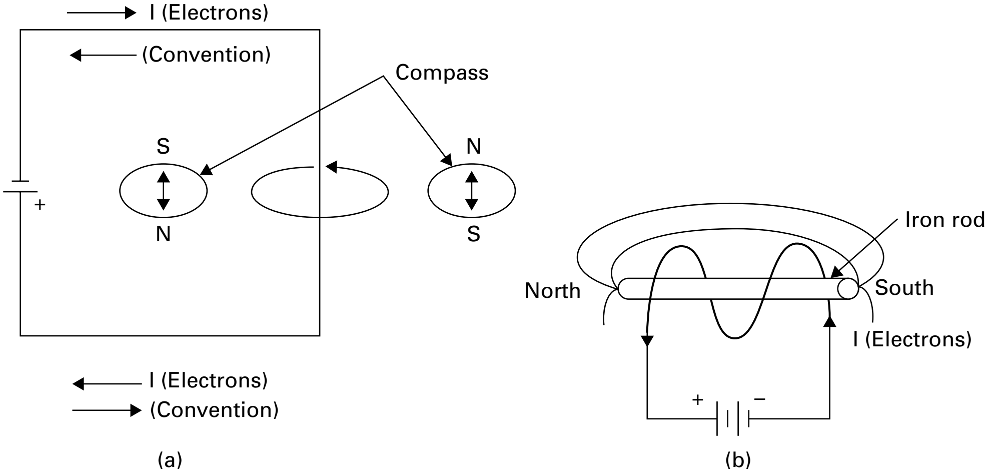


FIGURE 1.11 Magnetic field surrounding a current-carrying conductor: (*a*) Compass at right indicates the polarity and direction of a magnetic field circling a conductor carrying direct current. *I* indicates the direction of electron flow. Note: The convention for flow of electricity is from + to –, the reverse of the actual flow. (*b*) Direction of magnetic field for a coil or solenoid. (*After* [2].)

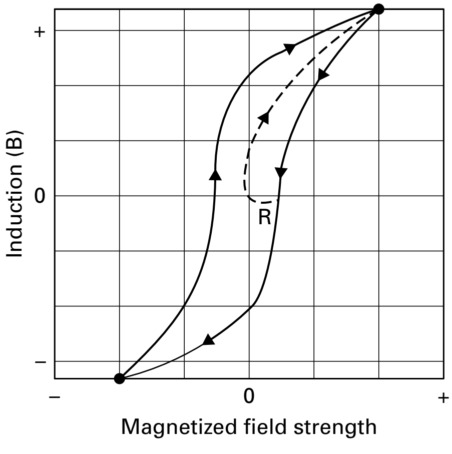


FIGURE 1.12 Graph of the magnetic hysteresis loop resulting from magnetization and demagnetization of iron. The dashed line is a plot of the induction from the initial magnetization. The solid line shows a reversal of the field and a return to the initial magnetization value. *R* is the remaining magnetization (remnance) when the field is reduced to zero. (*After* [2].)

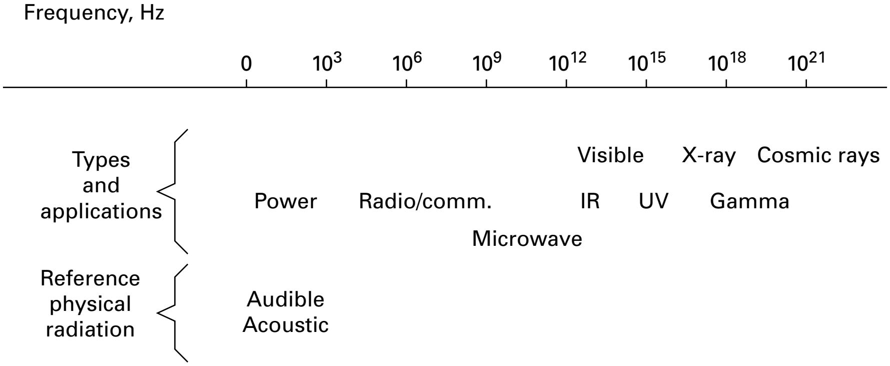


FIGURE 1.13 The electromagnetic spectrum. (*After* [3].)

Electromagnetic-Radiation Spectrum

The usable spectrum of electromagnetic-radiation frequencies extends over a range from below 100 Hz for power distribution to 10^{20} for the shortest X-rays [2]. Services using various frequency bands in the spectrum are shown in Figure 1.13. The lower frequencies are used primarily for terrestrial broadcasting and communications. The higher frequencies include visible and near-visible infrared and ultraviolet light, and X-rays.

The electromagnetic spectrum can be roughly divided into the following general categories:[1]

- **Low-end spectrum frequencies** (1 to 1000 Hz) Electric power is transmitted by wire but not by radiation at 50 and 60 Hz, and in some limited areas, at 25 Hz. Aircraft use 400-Hz power in order to reduce the weight of iron in generators and transformers. The restricted bandwidth that would be available for communication channels is generally inadequate for voice or data transmission, although some use has been made of communication over power distribution circuits using modulated carrier frequencies. The sound-transmission frequencies noted in Figure 1.13 are acoustic rather than electromagnetic.
- **Low-end radio frequencies** (1000 to 100 kHz) These low frequencies are used for very long-distance radio-telegraphic communication where extreme reliability is required and where high-power long antennas can be erected.
- **Medium-frequency radio** (100 kHz to 2 MHz) The low-frequency portion of the band is used for around-the-clock communication services over moderately long distances and where adequate power is available to overcome the high level of atmospheric noise. The upper portion is used for AM radio, although the strong and quite variable sky wave occurring during the night results in substandard quality and severe fading at times. Other uses include fixed and mobile service and amateur radio communication.

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[1] Note that specific spectrum division and classification terms have been developed and are in use worldwide. For our purposes here, however, these convenient general groupings will suffice.

- **High-frequency radio** (2 to 30 MHz) This band provides reliable medium-range coverage during daylight and, when the transmission path is in total darkness, worldwide long-distance service, although the reliability and signal quality of the latter is dependent to a large degree upon ionospheric conditions and related long-term variations in sunspot activity affecting sky-wave propagation. The primary applications include broadcasting, fixed and mobile services, telemetry, and amateur transmissions.
- **Very high and ultra-high frequencies** (30 MHz to 3 GHz) VHF and UHF bands, because of the greater channel bandwidth possible, can provide transmission of large amounts of information. Furthermore, the shorter wavelengths permit the use of highly directional parabolic or multielement antennas. Reliable long-distance communication is provided using high-power tropospheric scatter techniques. The multitude of uses include television, fixed and mobile communication services, amateur radio, radio astronomy, satellite communication, telemetry, and radar.
- **Microwaves** (3 to 300 GHz) At these frequencies, many transmission characteristics are similar to those used for shorter optical waves, which limit the distances covered to line of sight. Typical uses include microwave relay, satellite, radar, and wide-band information services.
- **Infrared, visible, and ultraviolet light** The portion of the spectrum visible to the eye covers the gamut of transmitted colors ranging from red, through yellow, green, and blue. It is bracketed by infrared on the low-frequency side and ultraviolet (UV) on the high side. Infrared signals are used in a variety of consumer and industrial equipments for remote controls and sensor circuits.
- **X-rays** Medical and biological examination techniques and industrial and security inspection systems are the best-known applications of X-rays. X-rays in the higher-frequency range are classified as *hard* X-rays or *gamma* rays. Exposure to X-rays for long periods can result in serious irreversible damage to living cells or organisms.

Audio Spectrum

For the purposes of this book, we will focus on the audio spectrum, which is generally accepted to range from 20 Hz to 20 kHz. It is important to note that advances in analog and digital technologies have pushed the lower limit of the audio spectrum to near DC—not that anyone can hear it (although listeners can *feel* it). Such advances have also extended the high end to well above 20 kHz—again, not that anyone can hear it. For digital systems sampled at 48 kHz (a common reference for professional applications), the theoretical upper boundary is 24 kHz due to the Nyquist limit[2].

In any chain of devices, the overall performance of the system is limited by the weakest link. In the case of vacuum tube audio amplifiers, the weakest link insofar

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[2] The Nyquist law for digital coding dictates that the sample rate must be at least twice the cutoff frequency of the signal of interest to avoid spurious patterns (aliasing) generated by the interaction between the sampling signal and the higher signal frequencies.

as bandwidth is concerned is usually the output transformer. The practical realities of transformer design and construction make it difficult to reproduce very low frequencies or very high frequencies. Having said that, a number of high-performance transformers have been developed that will faithfully reproduce waveforms from 10 Hz (or less) to more than 50 kHz (in a few cases well above 50 kHz).

Decibel Measurement

Audio signals span a wide range of levels [4]. The sound pressure of a rock-and-roll band is about 1 million times that of rustling leaves. This range is too wide to be conveniently accommodated on a linear scale. The decibel is a logarithmic unit that compresses this wide range down to a more easily handled range. Order-of-magnitude (factor-of-10) changes result in equal increments on a decibel scale. Furthermore, the human ear perceives changes in amplitude on a logarithmic basis, making measurements with the decibel scale reflect audibility more accurately.

A decibel may be defined as the logarithmic ratio of two power measurements or as the logarithmic ratio of two voltage measurements. The following equations define the decibel for voltage (E) and power (P):

$$dB = 20\log\frac{E_1}{E_2}$$

$$dB = 10\log\frac{P_1}{P_2}$$

There is no difference between decibel values from power measurements and from voltage measurements if the impedances are equal. In both equations, the denominator variable is usually a stated reference. Whether the decibel value is computed from the power-based equation or from the voltage-based equation, the result is the same.

A doubling of voltage will yield a value of 6.02 dB, and a doubling of power will yield 3.01 dB. This is true because doubling voltage results in a factor-of-4 increase in power. Table 1.1 shows the decibel values for some common voltage and power ratios.

Audio engineers often express the decibel value of a signal relative to some standard reference, rather than another signal. The reference for decibel measurements may be predefined as a power level, as in dBm (decibels above 1 mW), or it may be a voltage reference. When measuring dBm or any power-based decibel value, the reference impedance must be specified or understood.

It is often desirable to specify levels in terms of a reference transmission level somewhere in the system under test. These measurements are designated dBr, where the reference point or level is separately conveyed.

TABLE 1.1 Common Decibel Values and Conversion Ratios

dB Value	Voltage Ratio	Power Ratio
−40	0.01	0.0001
−20	0.1	0.01
−10	0.3163	0.1
−6	0.501	0.251
−3	0.707	0.501
−2	0.794	0.631
−1	0.891	0.794
0	1	1
+1	1.122	1.259
+2	1.259	1.586
+3	1.412	1.995
+6	1.995	3.981
+10	3.162	10
+20	10	100
+40	100	10,000

Dimensions of Hearing

The perception of sound is a complex process involving many variables [5]. *Loudness* is the term used to describe the magnitude of an auditory sensation. It is primarily dependent upon the physical magnitude (sound pressure) of the sound producing the sensation, but many other factors are influential. Sounds come in an infinite variety of frequencies, timbres, intensities, temporal patterns, and durations; each of these, as well as the characteristics of the individual listener and the context within which the sound is heard, has an influence on loudness.

Listening to a sound in the presence of another sound, which for the sake of simplicity we will call noise, results in the desired sound being, to some extent, less audible. This effect is called *masking.* If the noise is sufficiently loud, the signal can be completely masked, rendering it inaudible; at lower noise levels the signal will be partially masked, and only its apparent loudness may be reduced. If the desired sound is complex, it is possible for masking to affect only portions of the total sound. All this is dependent on the specific nature of both the signal and the masking sound.

Pitch is the subjective attribute of frequency, and while the basic correspondence between the two domains is obvious—low pitch to low frequencies and high pitch to high frequencies—the detailed relationships are anything but simple. Fortunately, waveforms that are periodic, however complex they may be, tend to be judged as having the same pitch as sine waves of the same repetition frequency. In other words, when a satisfactory pitch match has been made, the fundamental frequency of a complex periodic sound and a comparison sinusoid will normally be found to have the same frequency.

Sounds may be judged to have the same dimensions of loudness and pitch and yet sound very different from one another. This difference in sound quality, known as *timbre* in musical terminology, can relate to the tonal quality of sounds from specific musical instruments as they are played in live performance, to the character of tone imparted to all sounds processed through a system of recording and reproduction, and to the tonal modifications added by the architectural space within which the original performance or a reproduction takes place. Timbre is, therefore, a matter of fundamental importance in audio, since it can be affected by almost anything that occurs in the production, processing, storage, and reproduction of sounds. Timbre has many dimensions, not all of which have been fully identified or understood.