Elements of Computer Music

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Introduction

> *First and above all, an explanation must do justice to what is being explained, must not devaluate it, misinterpret it, belittle it, or distort it, in order to make it easier to understand. The question is not "What view of the phenomenon must be acquired so that it can be comfortably explained in accordance with one or another philosophy?" but precisely the reverse: "What philosophy will be required in order to live up to the subject, be on the same level with it?" The question is not how the phenomenon must be turned, twisted, narrowed, or crippled, so that it can be made explicable according to principles that we have in any case resolved not to go beyond, but: "To what point must our thought be enlarged in order to stand in proportion with the phenomenon?"*
>
> —F. W. J. von Schelling, *Philosophie der Mythologie* (1857)

Every human culture has developed—along with language—at least some form of visual art and music. Little can be said of the true origins of music because its roots are shrouded in the remotest of human antiquities. Music is, perhaps, more a *defining* characteristic of human beings than a passing phase in the evolution of intelligence.

The significance of music has been debated with varying degrees of heat throughout recorded history. All such debates, however enlightened, have ultimately failed to capture the essence of music for the simple reason that music expresses properties and states of mind that cannot be expressed in words.

The inability to state its significance in words has earned music both respect and a certain amount of trepidation. Among the ancient Greeks, the great philosopher-poet Plato repeatedly revealed his disquiet regarding music.

> Now we must not omit the full explanation of the difficulty with music. There is much more talk about musical imagery than about any other kind, and this is the very reason why such imagery demands more cautious scrutiny than any other. It is here that error is at once most dangerous, as it encourages morally bad dispositions, and most difficult to detect, because our poets are not altogether on the level of the Muses themselves. The Muses, we may be assured, would never commit the grave mistake of setting masculine language to an effeminate scale, or tune, or wedding melody, or postures worthy of free men with rhythms only fit for slaves and bondsmen, or taking the prose of a free man and combining it with an air or words of inappropriate rhythm. Not to say that they would never make a pretended presentation of a single theme out of a medley of human voices, animal cries, noises of machinery, and other things. Whereas our mere human poets tend to be only too fond of provoking the contempt of us who, in the phrase of Orpheus, are "ripe for delight," by this kind of senseless and complicated confusion. In fact, not only do we see confusion of this kind, but our poets go still further. They divorce rhythm and figure from melody, by giving metrical form to bare discourse, and melody and rhythm from words, by their employment of cithara and flute without vocal accompaniment, though *it is the hardest of tasks to discover what such wordless rhythm and tune signify, or what model worth considering they represent* [emphasis added]. Nay, we are driven to the conclusion that all this so popular employment of cithara or flute, not subordinated to the control of dance or song for the display of speed and virtuosity, and the reproduction of the cries of animals, is in the worst of bad taste; the use of either as an independent instrument is no better than unmusical legerdemain. So much for the theory of the thing.[1]

Plato, it would seem, was among the first and most significant to fall into the trap of confusing knowledge with language. For a musician "to discover what such wordless rhythm and tune signify" is among the easiest—not the hardest—of tasks, provided, of course, that the musician is not required to translate this significance into words. Words, no matter how skillfully employed, are impoverished when compared to the full range of human experience. To confound knowledge that can be stated in words with all knowledge is to confuse the map with the territory.

To be sure, knowledge is conveyed through its expression, but expression, like knowledge, has many forms. In modern science, for example, mathematics is often used both to investigate and to express fundamental concepts about nature. It is usually possible to recouch a mathematical statement in words without loss of any essential detail. But mathematics represents more than a precise and convenient shorthand. The power of mathematics is that it captures the essence of certain types of relationships in a way that reveals more than it conceals to anyone who is fluent in its principles. Yet it would be in most cases difficult, if not impossible, to attain mathematical insights through the use of words alone.

Without mathematics, for example, the study of the stars is called *astrology*, derived from the Greek roots *astro*, meaning "star", and *logos*, meaning "word or speech." *Astrology* therefore signifies "what can be said about stars." The scientific study of the stars, however, is called *astronomy*, from *astro* plus *nomy*, from the Greek

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[1] Plato, *Laws*, as trans. by A. E. Taylor, in *The Collected Dialogues of Plato*, ed. E. Hamilton and H. Cairns, (Bollingen Foundation, 1966). Reprinted with the permission of the copyright owners, J. M. Dent and Sons, London.

némein, meaning "distribute." *Astronomy* therefore signifies the system of laws governing or sum total of knowledge regarding the stars. Even though they are not used consistently in this way today, the *-logy* and *-nomy* suffixes distinguish neatly between the part of knowledge that can be expressed in words and the sum total of knowledge about a field.

The establishment of astronomy came, however, not with the advance of mathematics but with the advance of the telescope. Despite the fact that he is often miscredited with its invention, the Italian scientist Galileo Galilei (1564–1642) *applied* the telescope to the study of the stars, discovering along the way the four "Galilean" moons of Jupiter and the rings of Saturn. Galileo's real contribution to astronomy, however, was not the establishment of a few new facts about our natural environment but the correct *interpretation* of these observations as confirmation of the revolutionary ideas of Polish scientist Nicolaus Copernicus (1473–1543). Copernicus believed and taught—contrary to popular and official opinion at the time—that the earth was *not* the center of the universe but instead revolved around the sun, thereby contributing both a fundamental scientific insight and a new word to the English language to describe such radical ideas, that word, of course, being *revolutionary*. The Copernican revolution—as it came to be called—rested on an untested theory until Galileo actually saw its confirmation through a telescope; today Copernicus is honored as the father of astronomy and Galileo ias the founder of experimental physics and astronomy. Both were persecuted for the entirety of their lifetimes.[2]

It may seem strange to begin a discussion computer music with the distinction between astrology and astronomy, because music is a purely human activity, whereas the stars have existed since a few astronomical moments after the Big Bang. But the parallel is a strong one, for computers allow investigation of purely musical issues in a way that permits observations more precise than those available to the "naked ear" alone.

If I were to attempt the ostensibly impossible task of stating in words what music really is, I would suggest that music addresses a sense for which our minds are the primary (if not the only) organ: our sense of *time*. Music draws our attention to a detailed progression of moments, the significance of which is apprehended as an abstraction of the succession of momentary awarenesses that make up a human lifetime. Physiologically, our senses of hearing and touch are similar, because the basilar membrane in the ear is basically a highly enervated piece of skin with a correspondingly fine ability to discriminate vibrations at frequencies in a range that overlaps slightly with the sense of touch at our fingertips. We find music "touching" in the metaphorical sense partly because we perceive it through physical contact with mechanical vibrations of the atmosphere.

So much for the theory of the thing. The important parallel between astrology and astronomy on the one hand and music on the other is that the computer represents a technological advance that has clear application to the study of music in a way that has not been possible in the past. Because music is a temporal art, its proper study

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[2] It is interesting to note that the works of Galileo were removed only recently from the Index (a list of forbidden works) of the Roman Catholic church, the teachings of which he contradicted.

necessarily includes a method for capturing, representing, and interpreting information about successive moments of time.

One such technological advance occurred about a century ago with the advent of means for recording sound. Not only has sound recording drastically transformed the study of music (it is now possible to study music from all over the world by listening to recordings, for example), but it has also transformed the methods by which music is made in fundamental ways. In a 1925 composition titled *The Pines of Rome*, Italian composer Ottorino Respighi (1879–1936) incorporated a part for a "gramophone" recording of the songs of nightingales during an orchestral evocation of a predawn moment. This use of recorded sound in music was a precursor to the development of *musique concrète* in France, which was based on the juxtaposition of recordings of the "concrete" sounds of nature (as opposed to the "abstract" sounds of traditional musical instruments). Describing their 1952 composition of *musique concrète* titled *Erotica (Symphonie pour un homme seul)*, French composers Pierre Schaeffer and Pierre Henry wrote: "To record a symphony of human sounds. The man by himself becomes his own instrument: his voice, his shout, his breathing, his laugh, the sound of his throat being cleared."

Electrical and electronic musical instruments have also graced the musical horizon practically since the turn of the twentieth century. At first rather impractical due to the relatively large size of electrical and electronic components,[3] improvements in electronics technology allowed serious composers of the 1950s to begin the exploration of new types of "synthetic" sound as material for music, such as the historically significant *Studien* created by German composer Karlheinz Stockhausen.

What, then, is significantly different about computer music? The full answer to that question is the topic of the rest of this book, but the essential quality is one of *temporal precision*. Computers allow precise, repeatable experimentation with sound. In effect, musicians can now design sounds according to the needs of their music rather than relying on a relatively small number of traditional instruments. Further, computers act as an instrument of the mind, extending the principles of musical composition to the simultaneous consideration of many more levels of organization than is practicable with the "naked mind" alone. Computers also extend the capabilities of musicians to control the production of sound during live performance.

With that said, it should be quickly noted that we are not used to dealing with music with such an enriched means to control its every aspect. We still live in an age where the primary theory of music comes under the heading of "musicology." With computers we are gradually entering the age of "musiconomy."

To complicate matters, computer music is one of the most strongly interdisciplinary fields in existence, because it includes significant aspects of art, science, and technology. Which of these is emphasized depends largely on the objectives of each practitioner, although some elements of art, science, and technology come constantly into play to some extent. Insofar as the objective is to produce music, computer music

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[3] The Dynamophone, an inductance-based electrical musical instrument constructed in 1906 by Dr. Thaddeus Cahill, for example, apparently required several railroad cars for its transport.

is an art; if the objective is to understand music as a human activity, computer music is definitely more like a science. Finally, all computer music activity involves the use of the computer, with all of the associated technological implications.

In a famous lecture on the relationship between physics and mathematics, noted physicist Richard P. Feynman started with an apology to those in the audience who knew nothing about physics or nothing about mathematics because to discuss their relationship it is necessary to begin by assuming familiarity with what is being related.

We necessarily adopt the same approach here. It would be impractical to discuss the basics of music and the basics of computers while at the same time attempting to relate computers to music. It is therefore necessary to assume that the reader is both musically literate and "computer literate" from the outset in the sense of being able to read and write both music and computer programs. If you know music well but do not know how to program computers, do not despair, for computer programming is much easier to learn than music. If you know how to program computers but not how to read and write music, you might despair slightly, for acquiring musical fluency generally takes a long time. Fortunately, computers are ever more prepared to help in music instruction, but that is another topic.

From a musical point of view, computers turn abstractions into concrete perceptions. Computers are of interest to musicians, therefore, not in themselves but insofar as they provide a vital link between musical imagination and reality.

Simply stated, computer music is the art of making music with digital computers. Because computers have no fixed function, their role in music-making processes varies greatly. To develop a coherent view of how computers can be applied to music, we begin with a bird's-eye-level examination of the processes that constitute music. In this context it will be convenient to define a *process* as any agent or activity that transforms information from one form to another. This definition leaves open the possibility that the processor may alternatively be a machine, a human being, or some cooperative combination of both.

1.1 MUSICAL DATA AND PROCESSES

Figure 1-1 is a "word picture" that depicts primary relationships among various types of information (data) that exist in music, together with processes (defined here as transformations of information) that act on this information. The flow of information is characteristically clockwise around the circle shown, although interactions occur at every level. General information about music (called the "musical" knowledge base in Figure 1-1 is used as needed in the listening, composing, and performing processes, any of which may be interpreted here as actions of a human being, a machine, or a combination of both. General properties of sound and vibration (collectively referred to as the "physical" knowledge base in the figure) is relevant primarily to the operation of musical instruments and performance spaces. The instrument and room processes may rely on physical objects, or they may be abstractions of these objects embodied in computer programs.

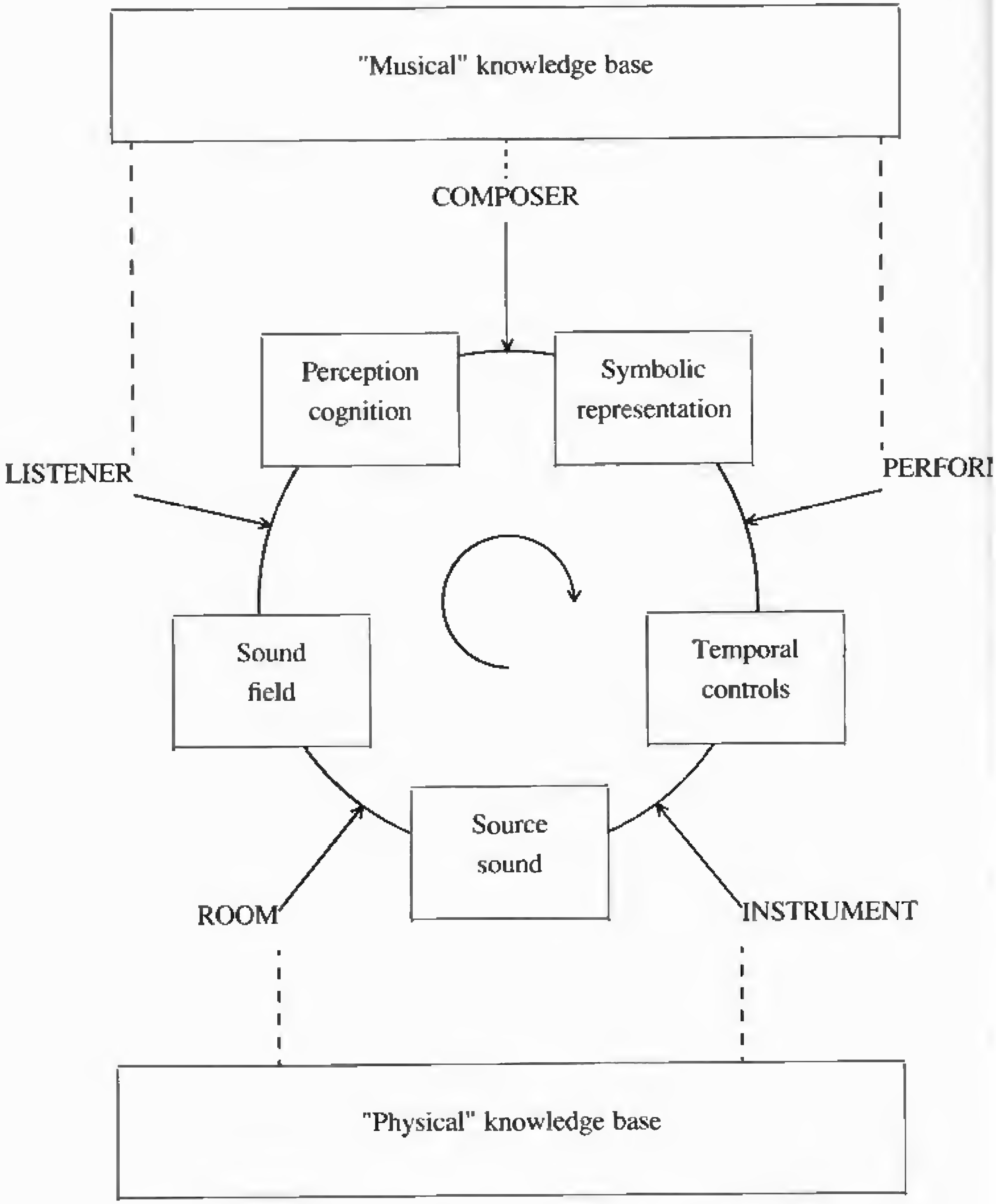

Figure 1-1 Musical data (in boxes) and processors (in capital letters). Data is information that may exist in many forms; processors may be human beings, machines, or a combination of both.

Stating that the process of musical composition may be undertaken by either a human being or a machine does not, of course, imply that people and computers are in any way equivalent. Rather, this definition is based on the premise that people and machines may at times carry out *equivalent tasks*. Although the distinction between what someone or something *is* versus what someone or something *does* would seem to be self-evident, it can sometimes be a source of confusion.[4]

1.2 MUSICAL THOUGHT

We start our exploration of computer music with consideration of the nature of musical thought. The box bearing the labels "perception" and "cognition" in Figure 1-1 does little to explain the profound nature of musical sensation and imagination.

On the most basic level, our senses gather information about our environment—this is the process of perception. Sensory information is used to aid in the various subtasks of survival. We must be able to detect dangerous situations in order to avoid falling off cliffs, being struck by moving objects, being attacked by dangerous beasts, and so on.

On a higher level, sensory information forms the basis for communication. While not all senses seem equally suited to communication, any available sense may be used, in principle, to pass messages. Spoken and written languages provide, among other things, the possibility of indirect knowledge about a great deal more than we could or would wish to experience directly.

On a yet higher level, sensory information forms the basis of the arts, with the most acute senses providing the most variegated forms of potential expression. The nature of artistic expression is a deep and multifaceted subject that goes well beyond the scope of this book. It is helpful to recall at this point, however, that virtually every human culture has developed—along with language—one or more forms of visual art and one or more forms of music.

Art is therefore a kind of commentary on human existence, one that extensively exercises the interpretive mechanisms (cognition) to which sensory information flows. Through art we gain not only indirect experience of actual existence but indirect experience of potential existence as well. In other words, art portrays imagination.

Acts of imaginative portrayal are limited in at least two important ways. The more fundamental of these limitations is human imagination itself. A simple example of such a limitation is to be found in the pervasive anthropocentrism that impedes our ability even to think about communication with intelligent nonhumans.

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[4] An example of such confusion occurred to me when I read the following prose in the introductory section of the fourteenth edition of the famed *CRC Standard Mathematical Tables*: "**Four-Place Antilogarithms**—Some computers prefer to use separate tables for determining antilogarithms; the table being entered from the margins with the logarithm and the number being found in the body of the table." I found "Some computers prefer" to be curious indeed until I learned from the preface to the volume that the Chemical Rubber Company first published this collection of mathematical tables and formula in the year 1938—the "computers" referred to were people!

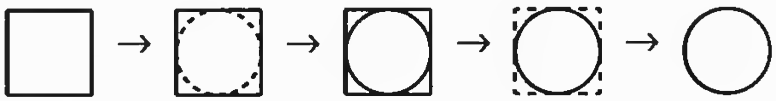
A less fundamental but no less important limitation on artistic portrayal involves the artist's quest to forge the means to express what has already been imagined. In short, we can easily conceive of things that we do not know how to realize. The annals of literary fiction—especially so-called science fiction—are filled with such imaginings. The importance of such expressed imaginings lies in the fact that they are necessary precursors to their eventual realization. In this sense, human imagination is the driving force behind human technology, not the other way around.

Computers are useful in the creation of music, therefore, because they allow the creation of music that cannot be realized in any other practical way. Consider, for example, the transformation of one sound into another.

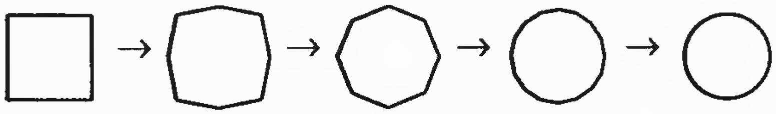
The notion of a *Klangfarbenmelodie* ("tone-color melody") is not new in music, yet the manner of its realization has generally been limited to the orchestral technique of gradually fading in one instrument while another fades out—a kind of instrumental "crossfade" (see Figure 1-2). At each intermediate point in time during the crossfade, we hear a sound mixture whose characteristics are dependent on the capabilities of the performers and instruments involved.

Other types of transformations are easily imagined, however. Suppose we imagine a clarinetist who begins to play middle C, but shortly after the beginning of the note the instrument gradually begins to take on the physical form of an oboe playing the same note (we ignore the physical—not to mention cognitive—difficulties such a transformation, might provide for the player). During each intermediate temporal interval in the transformation, we would hear a sound that gradually changes from that of a clarinet to that of an oboe. Such a transition would sound quite different from a crossfade.

We can construct a visual analogy to these two types of timbral transitions in the following way. During a crossfade, we perceive either or both of two well-defined shapes, as in the following diagram, where the square might represent the sound of the clarinet and the circle the sound of the oboe.

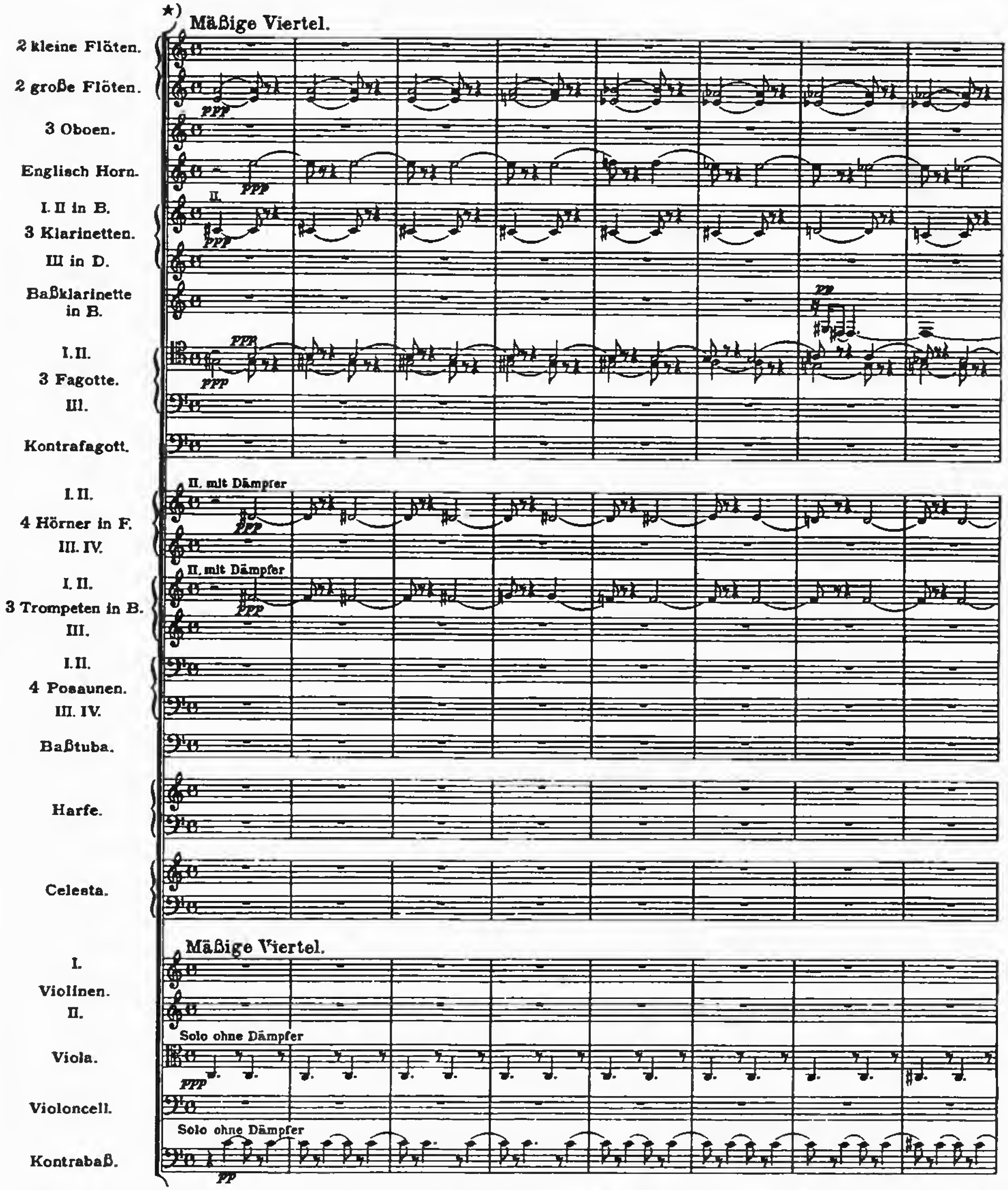


The following diagram represents not a crossfade but a gradual transformation of one shape (the square) into the other (the circle).



We can imagine an infinite number of "paths" by which we might transit from one sound to another, some of which might visit familiar sounds along the way but all of which visit the vast, largely unexplored territory that exists between the familiar ones. This is but one example of how computers enlarge the realm of musical possibility by allowing the realization of what otherwise can only be imagined.

III.
Farben.



Es ist nicht Aufgabe des Dirigenten, einzelne ihm (thematisch) wichtig scheinende Stimmen in diesem Stück zum Hervortreten aufzufordern, oder scheinbar unausgeglichen klingende Mischungen abzutönen. Wo eine Stimme mehr hervortreten soll, als die anderen, ist sie entsprechend instrumentiert und die Klänge wollen nicht abgetönt werden. Dagegen ist es seine Aufgabe darüber zu wachen, daß jedes Instrument genau den Stärkegrad spielt, der vorgeschrieben ist; genau (subjektiv) seinem Instrument entsprechend und nicht (objektiv) sich dem Gesamtklang unterordnend.

*) Der Wechsel der Akkorde hat so sacht zu geschehen, daß gar keine Betonung der einsetzenden Instrumente sich bemerkbar macht, so daß er lediglich durch die andere Farbe auffällt.

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Figure 1-2 "Farben (Sommermorgen an einem See)" from *Fünf Orchesterstücke* by Arnold Schönberg (Opus 16, 1909). In this landmark composition of twentieth-century music, Schönberg produces a "melody" of tone colors by continual reorchestration of sustained pitches. Reprinted with the permission of the copyright owners, C.F. Peters Corporation, New York. (© C. F. Peters, Leipzig. All rights reserved.)

1.3 COMPOSING

Traditional music composition, as we have defined it, is the process of producing symbolic representations of musical thought. Musical thought appears to be based on subjective interpretation of the temporal relationships of audible events. These relationships are perceived in at least three ways according to associated human sensory modalities involving the sense of hearing and short- and long-term memory.

The most rapid temporal events in music are associated with the vibrations of sound itself. Audible sound usually consists of a periodic or semiperiodic mechanical disturbance of the planetary atmosphere at rates of about 20 to 20,000 vibrations per second. Vibrations that occur at rates faster than about 20,000 times per second are not perceived as sound, and atmospheric disturbances that occur less frequently than about 20 times per second are perceived individually, if at all. Atmospheric vibration patterns that repeat themselves in regular, periodic patterns in the sonic regime tend to give rise to the sensation of definite *pitch*, while irregular vibration patterns tend to give rise to indefinitely pitched sonic sensations, often described as various qualities of *noise*. The strength, or *amplitude*, of these vibration patterns is generally related to the subjective sensation of loudness, while the detailed *shape* of sonic vibration patterns is perceived as tone quality, or *timbre*. Sounds are also perceived differently according to *spatial relationships* between sound sources and listeners, allowing us to form subjective impressions of the directions and distances from which sounds emanate. These four physical characteristics of sound,

- Vibration pattern repetition rate
- Vibration pattern amplitude
- Vibration pattern shape and
- Sound source location relative to the listener

together with their subjective correlates,

- Pitch (definite or indefinite)
- Loudness
- Timbre
- Localization

form the psychophysical basis for musical sound.

On a broader temporal level, sounds begin and end in patterns that are perceived as musical events such as notes, rhythms, tempo, and meter. Music is often organized around a periodic event rate called a beat, or *pulse*. The range of acceptable pulse rates in music is related to characteristic periodicities of the human body, especially by comparison to the rate of the "natural" visceral human clock, that is, the rate at which the human heart pumps blood (about 72 beats per minute, or 1.2 beats per second). Pulse rates in music vary around this frequency over about the same range as the heart rate also varies, from about 30 beats per minute (0.5 Hz) during sleep or deep meditation to about 200 beats per minute (3.33 Hz) during vigorous exercise. The establishment of a pulse rate in music serves the important function of allowing performers to play together, because the regularity of the pulse can be used to anticipate sonic events in the immediate future as well as to suggest the organization of events in the immediate past. For these reasons, a musical pulse may go no faster than human performers can readily synchronize and may go no slower than human listeners can immediately remember.

Musical pulses are typically organized into further temporal groupings, or *meters*, thereby establishing a yet slower periodicity (or quasi-periodicity) in music. Pulses are also subdivided harmonically to provide the basis for *rhythm*. Harmonic subdivisions of the pulse may extend upward in frequency to about 10 to 15 events per second and are limited mainly by the physical characteristics of human performers and musical instruments. Temporal event patterns may synchronize well with expectations induced in the listener by an obvious pulse, or they may purposely thwart such expectations, giving rise to the ''offbeat'' musical concept called *syncopation*. Certain types of music, especially traditional dances, are based not only on particular meters but on particular rhythms as well. A musical meter may be regular, like the consistent triple-pulse grouping of a waltz or duple-pulse grouping of a march, or it may be consistently irregular, such as the constantly shifting meter of the great ballets of Igor Stravinsky.

Some composers have explored other types of temporal organizations for music in the five-octave range from 0.5 to 15 Hz. The pseudorhythms of human speech have often been employed in this context, as well as various other types of continuous (rather than harmonic or hierarchical) subdivisions of pulses. Such methods of temporal organization are often plagued with difficulties of synchronization among multiple performers but work well for solo performers or in cases where precise synchronization is irrelevant.

Longer-term temporal organizations occur in music at the level of the *phrase*, which is associated with the time between breathing during human speech (normally about 2 to 15 seconds). Musical phrases are continuous utterances, not in any strict sonic sense but in the sense of continuous availability of breath and hence connectivity. Of course, musical phrases for certain instruments are not necessarily limited to human lung capacity, but short-term human memory has about the same temporal proportions, making musical ''phrases'' a common constituent of much music. Other long-term musical effects include the gradual change of some overall musical characteristic such as loudness (*crescendo* and *diminuendo*), and tempo (*accelerando* and *rallentando*).

The longest-term level of musical organization is commonly called *form*. Forms include the ''ABA'' phrase structure of simple songs (such as “For He’s a Jolly Good Fellow”) to complex and involved ''dramatic'' forms such as sonatas (exposition-development-recapitulation-coda, typified in much keyboard music by Mozart) and ''narrative'' tone poems (such as Richard Strauss's *Till Eulenspiegel's Merry Pranks* and Modest Mussorgsky's *Pictures at an Exhibition*).

The following table summarizes the categories of temporal variation in music.

Approximate Levels of Temporal Variation in Music

Duration (Period)	*Repetition Rate (Frequency)*	*Typical Examples*
> 1 hour	(once per evening)	Grand opera
5 – 60 minutes	(a few per evening)	Symphonies, sonatas
0.5 – 20 minutes	(a few per composition)	Formal musical structures, movements
2 – 60 seconds	(many per composition)	Phrases
0.067 – 10 seconds	0.1 – 15 Hz	Events (notes, rhythms, pulses, meters)
50ms–50μs	20–20,000 Hz	Sound (pitch, loudness, timbre, localization)

This, then, is the temporal domain of the composer of music. The task of composing, as we have defined it, lies in finding symbolic representations for musical events on some or all of these temporal levels of variation.

Alternative notations for music may be characterized by the ways they encode musical thought. Some notations can represent specific qualities of perceived sound (such as pitch) in terms of what should be heard as a function of time. Other notations represent specific instructions to performers regarding actions they are to take with their instruments (such as fingerings, bowings, mutings, and articulatory instructions). Still other notations describe general and often abstract qualities of the music (such as tempo markings and intended emotional states to be induced).

By far the most common notation for musical thought is the traditional and well-entrenched system of staves, clefs, quarter notes, flats and sharps, and barlines. So-called common practice notation (CPN) for music has the built-in advantage of being well-understood by virtually everyone who has received formal training in Western music as well as countless others who have "picked up" music notation as one "picks up" a second or third written language. Another advantage of CPN is that the bulk of an extremely rich and varied musical literature ranging from about the sixteenth century to the present is expressed in it.

CPN is essentially a highly encoded abstract representation of music that lies somewhere between instructions for performance and representation of the sound. Before the advance of CPN, music was commonly notated with so-called *tablature* symbols that described more or less directly what a performer had to do to play it on a particular instrument.

Some forms of tablature notation survive today, most notably the symbols that show actual (if somewhat simplified) fingerings for guitar chords on popular sheet music. The disadvantage of tablature notation, then, is its limitation to specific instruments—the same composition would have to be notated differently for a guitar and a piano, for example.

Because it encodes just pitch, duration, and dynamics, a CPN score may be more easily carried from instrument to instrument as long as the instruments have similar capabilities: harpsichord music may be played on the piano, flute music may be played on the oboe, and so on. Instruments of dissimilar capabilities may all share a fairly compatible notation as well, making it relatively straightforward to arrange a piano score for orchestra and vice versa. Special extensions to CPN can be made for specific instruments as well, such as allowing two five-line staves for pianos and harps, three staves for the pipe organ, and a variety of convenient clefs (today only the treble, alto, tenor, and bass are in common use) according to the pitch range of the instrument.

CPN encodes music in much the same way as written language encodes spoken language. The proper correspondent of CPN in written language is not the text of a novel, however, but the script for a play. Music notation is not meant to be "read"; it is meant to be "read aloud." The CPN equivalents of stage directions are given, typically in quaint Italian terms such as "*presto con fuoco*," "*largo e mesto*," and (one of my favorites) "*allegro giusto, nel modo russico; senza allegrezza, ma poco sostenuto.*"

Despite its considerable advantages, CPN has disadvantages as well, especially as a notation for computer music. For one thing, CPN is built around the (historically reasonable) idea that instrumental timbres and other characteristics remain fixed in time. CPN therefore does little to represent tone quality, or timbre. It would be difficult to extend CPN to describe the transformation of timbre discussed earlier. A lengthy written description of the intended effect could be attached to a CPN score (such descriptions are often found in modern scores), but that is just the point: the basic notation no longer serves to describe the intentions of the composer very well.

Another disadvantage of CPN is that it describes pitches organized in two basic types of systems: *tonal* systems in which single pitches are primary, and *well-tempered* systems, which admit enharmonic equivalents. Pitch, however, is a *continuum*, while its representation in CPN is inherently *categorical*. Such restrictions on the notation of pitch are entirely appropriate to instruments whose pitch properties remain fixed in time (such as keyboard instruments), but they become increasingly intolerable as the pitches obtainable from instruments become more precisely controlled.

The reasons to retain CPN as a music representation break down altogether when a composer is notating music for machine realization. In the generalized context of computer music, CPN remains useful as a link to human performers (when they *are* human) and little else.

1.4 PERFORMING

Performing music, as we have defined it, is the task of transforming symbolic representations of musical thought into the physical actions necessary to operate a musical instrument so that the specified musical thoughts are realized in sound. While much is known about the symbolic representations (scores) themselves, and a great deal is known about the operating characteristics of musical instruments, very little is known about the nature of performance itself. Clearly, a performer may use a score as a guide to the performance of a particular composition of music. In addition, performers use a great deal of general knowledge about music to make decisions about the most effective manner in which to perform a particular composition. Performers also use acoustic feedback to adjust their actions to the circumstance of a performance.

Consider the notion of a *staccato* (literally, "detached" or "separate") note. In CPN, a composer specifies that a note is to be played staccato by placing a dot over or under it, indicating that it is to sound disconnected from notes that follow it. Such disconnection is typically achieved by operating a musical instrument so that the duration of the note is shortened relative to its ''normal'' duration, placing a tiny region of silence (or near-silence) between that note and the next. It is the performer's task to decide whether this shortened version of the note is to have 10, 50, or 90 percent of its nominal duration. How does a performer make such a choice?

Among the factors that will determine the ''duty cycle'' of the staccato note are the operating characteristics of the instrument. Some musical instruments such as the piccolo flute and violin ''speak'' relatively quickly, giving the performer a broad range of choice in determining note durations even at rapid tempi. Other instruments such as the tuba and contrabass speak relatively slowly, which places a lower bound on the range of available durations.

Even more important, though, is the reverberant quality of the listening room in which the music is played. In a room with a long reverberation time such as a cathedral, notes of even brief duration tend to ''ring'' for protracted periods of time. In a dry recording studio, notes die out almost immediately after the instrument stops vibrating. In the former environment, a performer is likely to play the same staccato note much shorter than in the latter, because the responses of the rooms will tend to make these two ''interpretations'' sound equivalent to a listener. Furthermore, the performer will be justified in doing so, because the different manners of performance will both produce precisely what is indicated in the score: a note detached from its successor by a little silence. At least in a certain sense, the room itself is part of the instrument that the performer has to play.

The details of performance have been little studied in any quantitative way because musical performance, unlike composition, occurs in real time. Until recently, therefore, it has been virtually impossible to unravel with any degree of precision what performers actually do . A basic part of musical training consists of learning to take musical dictation, which is the act of writing down CPN to describe a musical performance. Sufficient practice in dictation allows musicians to reconstruct the musical score from which players read by listening. But as in taking dictation of human speech, the notation reveals only the stimulus to which the performers are presumably reacting and not the nature of the reaction itself. In other words, CPN represents much less information than is contained in an actual performance.

Musicians use at least four basic types of information during standard performance:

- Information from the score prepared by a composer
- Information about the nature and response of musical instruments
- General knowledge about musical performance practice
- Acoustic feedback from the performance as it unfolds in a particular room

Performers may also monitor the sounds and actions of other musicians with whom they play in concert, including a conductor whose purpose is to resolve performance interpretation issues during rehearsals and to provide reminders (cues) and interpretive synchronization gestures during performance.

The result of all of these considerations is some type of *inflection* for virtually every note executed by a musician during performance, for example:

- Notes may be accented slightly with tonguing or bowing articulations.
- Rhythms may be distorted slightly (*rubato*) to provide agogic accentuation or de-accentuation of certain notes.
- Pitches may be inflected by a characteristic but variable trajectory.
- Vibrato or tremolo may be applied in a dynamically changing manner during note events.
- Dynamic levels may be adjusted to match those of other instruments or to enhance contrast.
- Specific but unindicated playing techniques may be invoked, consciously or unconsciously, (such as bowing or plucking near the fingerboard or bridge rather than the usual place), to enhance brightness, contrast, or manual feasibility.

This virtually endless list of techniques for expressive innuendo comprises the performer's art and task. Performers are at once beset by the composer's specifications, the historical weight of performance practice, the gestural indications from a conductor, the sounds and mechanical functions (and malfunctions) of an instrument, the vagaries of room acoustics, and the expressions on the faces of the audience.

Performers also are known at times to dispense with composers altogether and to undertake improvisatory control of the formal aspects of the music as well. This is necessary to make sure that they have enough to do during performance. More seriously, it is clear that musical performance is one of the most complex tasks of which human beings are capable, and a better understanding of it will undoubtedly require considerable further research.

1.5 INSTRUMENTS

Musical instruments transform the actions of one or more performers into sound. The characteristics of the sound generated depend on the structure of the instrument as well as the manner in which it is played.

According to the lore of musical acoustics, traditional musical instruments fall into one or more basic categories according to their construction:

- *String instruments*, in which one or more stretched strings are made to vibrate, typically by bowing, plucking, or striking, in conjunction with resonating boxes or sound boards (or both)
- *Wind instruments*, in which fipples, pressure-excited reeds, or buzzing lips are coupled with resonating air columns
- *Percussion instruments*, which include virtually any object that may be struck, typically consisting of bars, plates, or stretched membranes and associated resonators

- *Voices*, which consist of the vocalizing mechanisms of human beings and other animals

In each case, a typical traditional musical instrument consists of an *excitation source* that can be made to oscillate in controllable ways and a *resonating system* that acts to couple these vibrations to the surrounding atmosphere; in so doing, the resonating system also affects the precise patterns of vibration.

Traditional musical instruments are characterized by the range of available pitches under various types of playing conditions, the manners in which the instrument may be usefully played together with the types of sounds associated with these playing techniques, and "personality" characteristics related to musical traditions and idiosyncrasies associated with each instrument.

Computers have been used extensively both to study the operation of traditional musical instruments and to explore nontraditional ways to pattern sound vibrations in musically useful ways. Computer sound synthesis for music generally falls into one or more of four basic categories:

- *Additive synthesis models*, in which elemental sound components (such as sine waves) are added together in time-varying ways
- *subtractive synthesis models*, in which complex sound sources (such as harmonic-rich waveforms, white noise) are subjected to the "whittling away" effect of time-varying digital filters
- *Nonlinear synthesis models*, in which a nonlinear process (such as frequency modulation) is used to synthesize a complex waveform in ways controlled by time-varying parameters
- *Physical synthesis models*, in which the mechanical operation of a real or imaginary instrument is simulated via the (differential equation) techniques of mathematical physics

In addition to these four basic methods of synthesis, the techniques of *digital signal processing* may be applied to virtually any digitally recorded sound, creating the possibility of a kind of *computer musique concrète*. Any and all of these techniques may be—and often are—combined.

The use of the computer as a musical instrument, both in real time and in nonreal time—is one of the most extensively explored subtopics of computer music to date. Even so, the surface of the sonic possibilities of the computer as a source of musical sound has only been scratched.

1.6 ROOMS

No matter how sound is synthesized with a computer, we normally hear it over loudspeakers or headphones. The sound that comes from the loudspeakers can be conceived either as a source (the loudspeaker) in a room (the listening space) or as a reproduction of a sound source in a different (and possibly synthetic) sonic environment.

In the first case, the only room acoustics that come into play are those of the room in which we listen. This situation is analogous to listening to any electronic instrument (such as a Hammond organ) in a sonic environment (such as a concert hall) and is essentially similar to listening to any other instrument playing in that room.

In the second case, however, we can simulate the action of a sonic environment with properties different from those of the playback space. A simple example of this involves listening to almost any orchestral recording played back over loudspeakers in a living room. We hear not only the sounds produced directly by the instruments but the reverberant effects of the concert hall in which the recording was made as well. Without too much imagination (it sometimes helps if we close our eyes), it is possible to hear the orchestra as it sounded in, say, Carnegie Hall, as opposed to how it would sound in our living room (assuming it would fit). A good playback system and recording may even allow us to locate individual instruments in this unseen acoustic space in terms of the distance and direction from where we are listening to the sound source, or instrument.

Limited synthesis of illusory acoustic space can be achieved with echo and reverberation units such as those commonly used in conjunction with electric guitars. A by-now classic debate in sound recording technique deals with whether it is better to place a few (ideally two) microphones at propitious locations in a concert hall or whether the music is better served by "close-miking" every instrument so that the balance of the instrumental sounds is brought under control of the recording engineer as well as the performers. This debate could never have survived long enough to become "classic" unless both methods had true advantages as well as disadvantages, not to mention the fact that the ultimate evaluation of the results is highly subjective and therefore variable according to individual tastes.

The techniques of digital signal processing can be brought to bear on the simulation of the reverberant characteristics of unseen listening environments, giving rise to the notion of an illusory acoustic space into which sounds may be projected. Thus it is possible to compose computer music in terms of the auditory spatial relationships among sounds as well as their pitch, timbre, duration, and so on. Even more striking is the ability to synthesize spatial relationships in a dynamic manner, so that sounds may seem to "move around" in an illusory acoustic space whose properties may vary arbitrarily as time goes by.

LISTENING

Our ability to use computers to affect perceived properties of sound rests on our understanding not only of sound but on the way in which it is heard by listeners as well. The relationship between the physical properties of sound and the manner in which it is perceived and understood by human beings is a subtopic of the general interdisciplinary field of psychophysics known as *psychoacoustics*. Because the physical properties of sound and the perceptual mechanisms of human beings are complicated in themselves, their interrelationship can be quite complex. The three basic elements of hearing may be represented schematically as follows:

Sound waves → auditory perception → cognition

Sound waves normally travel in three dimensions, though we often simplify discussions of them by assuming that they travel only in one. Furthermore, a musical instrument such as a violin emits slightly different sounds simultaneously in all directions. The sound radiation pattern of a given instrument interacts with nearby objects to form a sound *field* in a given listening enclosure. Because music is normally played indoors, the properties of this sound field are quite complex, being affected by the temperature,[5a] humidity,[5b] composition,[5c] and density[5d] of the air; the size,[5e] shape, surface texture,[5f] and composition[5g] of walls, floors, and ceilings; and similar properties of any objects within the listening space. At every point in a listening space, the air pressure varies slightly above and below the atmospheric mean[6] in a slightly different way.

When we listen to a performance in a concert hall, we are literally "bathed" in a complex sound field. Our ears "sample" this sound field at two points separated by less

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[5a] A useful formula showing the relation of sound propagation speed to temperature is

$$c \approx 331.7\sqrt{1 + T_C/273} \approx 331.7 + 0.61T_C$$

where c is the speed of sound in meters per second and T_C is the air temperature in degrees Celsius (°C). This equation states that the speed of sound in a freezing room (0°C) is about 331.7 meters per second, while the speed of sound in a hot room (40°C) is $331.7 + 0.61 \times 40 = 356.1$ meters per second, a variation of just over 7.3 percent. At "normal" room temperatures of around 20°C, sound travels at about 344 meters per second.

[5b] Sound travels slightly faster in wet than in dry air, but the range of speed variation is only on the order of 1.5 percent from 0 to 100 percent relative humidity, so this effect can be ignored under most circumstances. Even this small effect, however, can affect the "spectrum balance" of the reverberant sound in a concert hall.

[5c] Normal dry air is approximately 78 percent nitrogen, 21 percent oxygen, and 1 percent argon by volume, except, perhaps, in Los Angeles.

[5d] It is interesting to note that variations in air pressure do not substantially affect the speed of sound and that all frequencies travel at essentially the same rate, though high frequencies are more readily absorbed and scattered by molecular processes than low frequencies.

[5e] Sound waves readily *diffuse* around objects that are small compared to the sound wavelength, making it possible, among other things, to hear around corners.

[5f] Rough surface textures tend to "trap" sound, especially at high frequencies, while smooth textures tend to reflect sound according to the basic physical law that the angle of reflectance is equal to the angle of incidence.

[5g] Diffraction effects cause more sound to be reflected from surfaces made of a material in which sound travels faster than from a material in which sound moves more slowly. Thus more sound is reflected from a smooth steel wall, than from a smooth wooden wall (sound travels at about 5250 meters per second in steel, about 4100 meters per second in maple wood).

[6] The smallest variation in air pressure that the ear can detect is on the order of 10^{-10} (one ten-billionth) of the mean atmospheric pressure, making it a very sensitive instrument indeed. Furthermore, the largest pressure variation that the ear can tolerate without pain is on the order of 10^{-4} of the mean atmospheric pressure, allowing the ear to operate over an amplitude range of 10^6 to 1. Because sound *intensity* is proportional to the square of the pressure variation, the numbers can seem even more impressive: the ear can detect certain sounds with an intensity of about 10^{-12} watts per square meter and withstand sounds at an intensity of about 1 watt per square meter, for an intensity range of 10^{12} to 1.

than 20 centimeters. The irregular shape of our *pinnae* (outer ears) allows us to distinguish slightly among sounds coming from different directions (front, above, and behind), and the two ears oriented in nearly opposite directions differentiate between sounds coming from the left and right.

Sound waves travel through the air, past the pinna, and into the outer ear canal (meatus), where they strike the timpanic membrane (eardrum), which vibrates sympathetically (see Figure 1-3). A chain of three small bones (middle ear) attached to the inner surface of the timpanic membrane transmits the vibrations to another membrane stretched across one of the openings of the inner ear, or cochlea (so called because it has a spiral shape similar to that of a snail). This membrane is called the oval window.

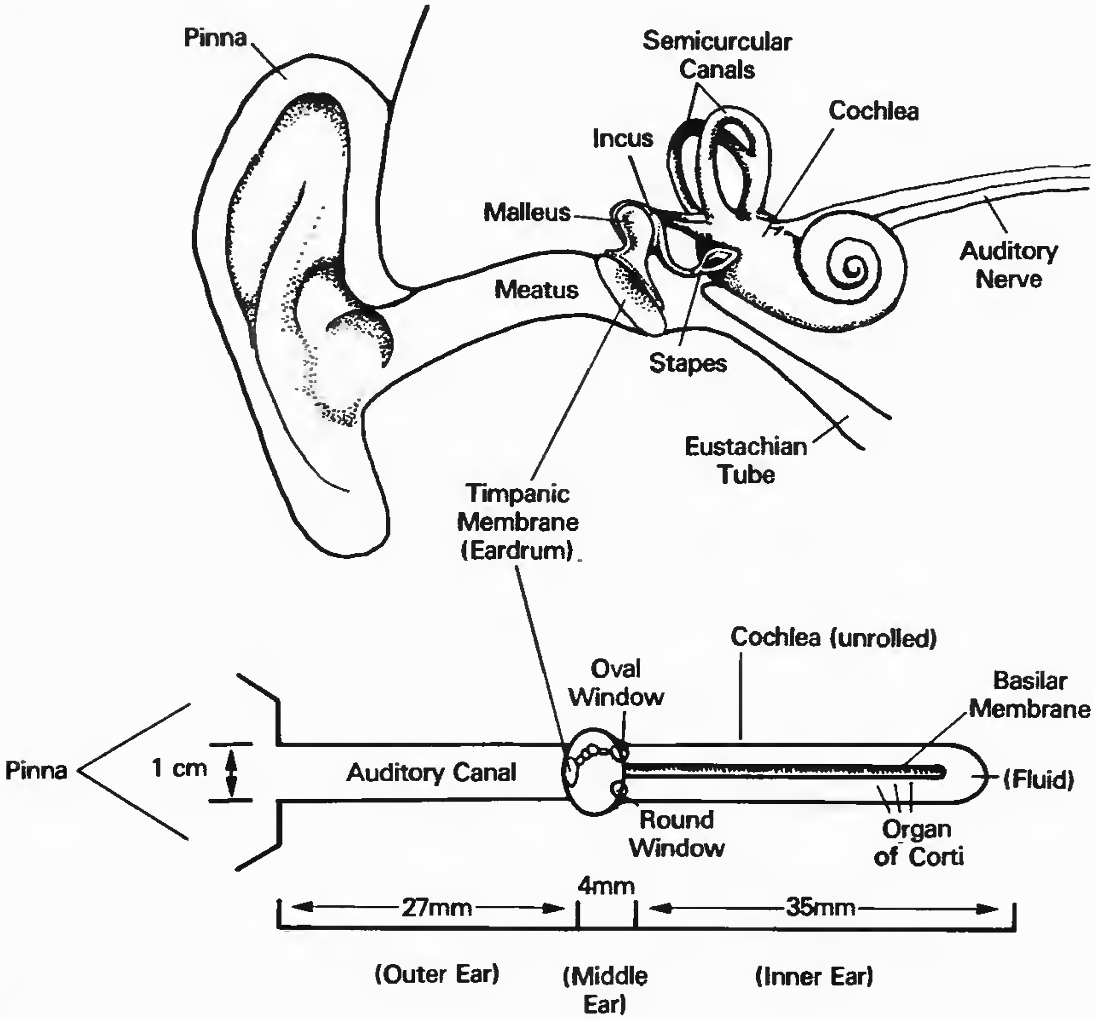

Figure 1-3 The ear.

The cochlea is hollow and filled with fluid. When the oval window vibrates, it produces compression waves in the cochlear fluid. Running through the center of the cochlea is the basilar membrane, which is lined on both sides with about 30,000 hair cells called the organ of Corti. These hair cells are actually frequency-specific nerve endings that are sensitive to forces produced by motion in the cochlear fluid. They generate electrical nerve impulses that exit the cochlea via the massive nerve bundle known as the auditory nerve. The auditory nerves from both ears run toward each other and into the auditory cortex where the signals are interpreted as speech, noise, music, and so on. There is increasing evidence that information from both ears is temporally correlated via "crossover" connections between the two auditory nerves before they enter the brain; this correlation information thereby enters the brain at practically the same time as the information from the ears themselves.

The eventual awareness of sound as music occurs on the highest level of nervous system processing—in the brain. It is essential to distinguish among the physical characteristics of the sound itself, the way in which the sound is perceived, and the eventual recognition and interpretation of the sound on a cognitive level (see Table 1-1).

Table 1-1 Physics→perception→cognition correlates of musical sound

Physics	Perception	Cognition
Air	Ear	Mind (knowledge + judgment)
Existence	Detection	Awareness
Sound	Sensation	Music
Intensity	Loudness	Musical dynamic
Frequency	Pitch	Pitch class
Spectrum	Timbre	Instrument recognition
Radiation	Localization	Subjective spatial map
Content	→	Form

As an example of the trichotomy among the physical, perceptual, and cognitive aspects of musical sound, consider the differences among sound intensity level, loudness, and musical dynamic.

Sound *intensity level* (IL) is measured in decibels above the threshold of hearing at 1000 Hz for acute listeners (10^{-12} watts per square meter) according to the formula

$$\text{IL (in dB)} = 10 \cdot \log_{10} \frac{I}{I_{\text{ref}}} \tag{1-1}$$

where I is the intensity in watts per square meter and I_{ref} is 10^{-12} watts per square meter.[7] The well-known Fletcher-Munson curves shown in Figure 1-4 portray the variable sensitivity of human hearing at different frequencies, particularly at low intensity levels. Each Fletcher-Munson curve relates the physical intensity levels needed at various frequencies to produce a perceived sensation of equal loudness. By convention, the individual curves are labeled with their value at 1000 Hz—this value is called the *loudness level* (LL) expressed in *phons*. Thus a loudness level of 60 phons refers to all of the intensity levels along the 60 phon curve in Figure 1-4 (a sound with an intensity level of about 70 dB at 100 Hz is as loud as a sound with an intensity level of about 58 dB at 4000 Hz; both sounds have a loudness level of 60 phons).

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[7] Intensity level is equivalent to decibels of sound pressure level (dB SPL) measured with respect to a pressure variation of 0.0002 dynes per square centimeter, or 2×10^{-5} newtons per square meter.

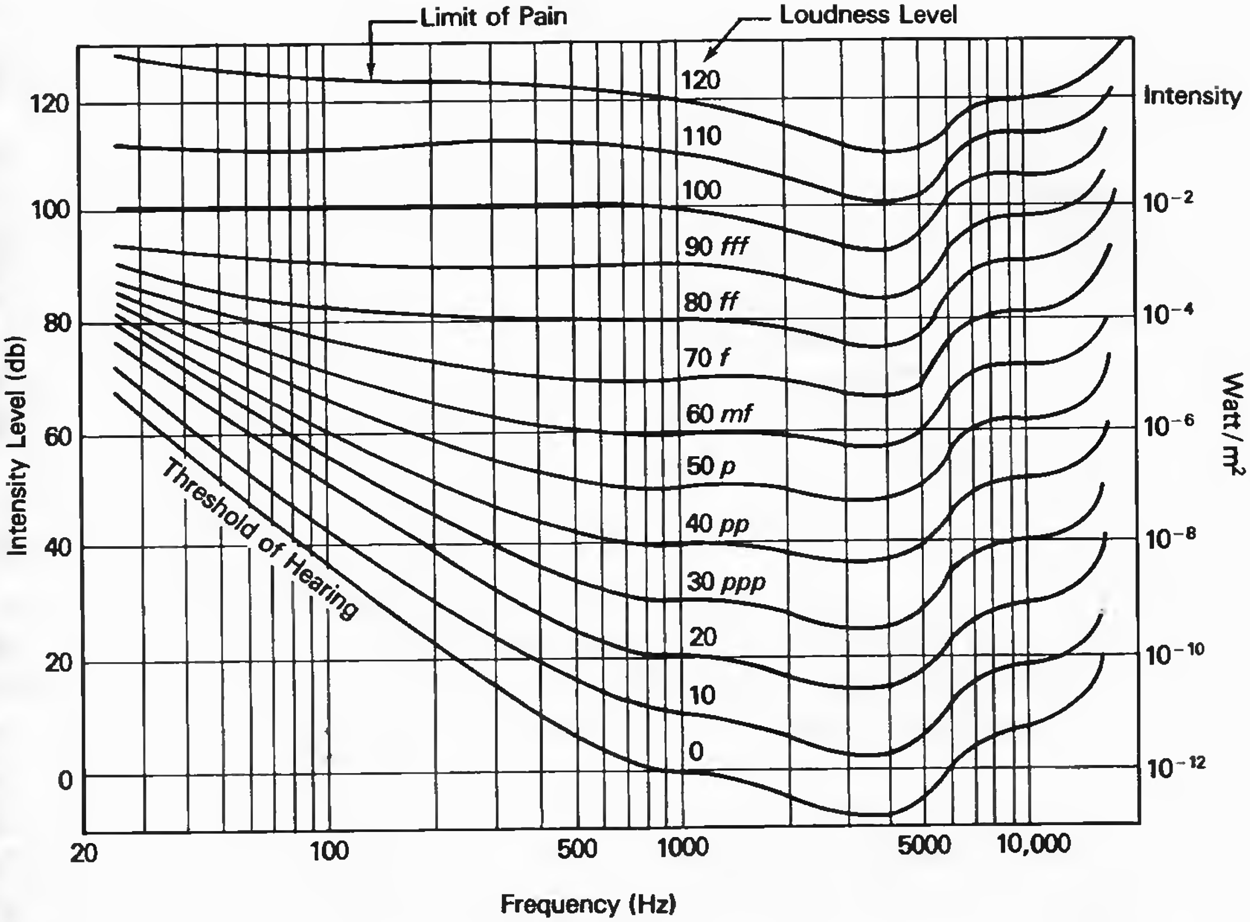

Figure 1-4 Fletcher-Munson curves of equal loudness level (isophons).

Both intensity level and loudness level refer only to the *physical* intensity of a sound. Knowing the intensity level of a sound is not sufficient to determine its perceived loudness, because that will depend on frequency. The loudness level of a sound tells us the intensity level of a 1000-Hz tone that will be equally loud. Does knowing the loudness level of two tones allow us to conclude anything about the relationship between their perceived loudnesses? In other words, because each 3 dB is an approximate doubling of intensity, can we conclude that a tone with a loudness level of 53 phons is twice as loud as a tone with a loudness level of 50 phons?

Unfortunately, the answer is no. The subjective scale of comparative loudness has nothing whatever to do with the so-called loudness level. To compare the loudnesses of two or more tones, we must use the measure of subjective *loudness* (L), which has units called *sones*. On this scale, a sound with a loudness of 2 sones is twice as loud as a sound with a loudness of 1 sone, a sound with a loudness of 100 sones is twice as loud as one with a loudness of 50 sones, and so on. Loudness has been shown to be approximately proportional to the cube root of intensity according to

$$L \approx C \times \sqrt[3]{I} \tag{1-2}$$

where L is (subjective, perceived) loudness, I is intensity in watts per square meter, and C is a constant that depends on frequency. According to this relationship, a doubling of loudness requires an eightfold increase in intensity. Because

$$10 \log_{10} 8 = 9.03 \ldots$$

we see that a doubling of perceived loudness requires an intensity level (or loudness level) increase of about 9 dB.

In other terms, we might increase the sound intensity eightfold by enlisting eight identical instruments to play the same note. According to relationship (1-2), these eight instruments playing together will sound just twice as loud as a single instrument playing alone—a prediction that is in good accord with musical experience. If the instruments play different notes, however, the situation is more complicated.

The loudness of two or more frequency components is proportional to the cube root of their total intensity only when the frequency components fall within the same *critical band* according to the relationship

$$L \approx C \times \sqrt[3]{I_1 + I_2 + I_3 + \cdots} \qquad (1\text{-}3)$$

where $I_1, I_2, \ldots,$ are the intensities of the individual components.[8] If the frequency differences among the components exceeds the critical band, a better prediction of the total subjective loudness is obtained by adding up the loudnesses of each individual component according to

$$L \approx C \times \sqrt[3]{I_1} + C \times \sqrt[3]{I_2} + C \times \sqrt[3]{I_3} + \cdots \qquad (1\text{-}4)$$

Two frequency components of equal intensity will therefore sound louder if they are separated by a perfect fourth (more than a critical band) than if they are separated by a minor second (less than a critical band).[9] Finally, when the separation of the frequency components is very large, the loudness of multiple tones is approximated well simply by the loudness of the loudest among them.[10]

From this discussion we can see that the relationship between perceived loudness and physical intensity is fairly complicated. If we now forge ahead into how the mind attributes a musical dynamic level to the complex tone of a musical instrument, we find that the situation becomes still more complicated.

The tone quality, or *timbre*, of most traditional musical instruments changes with dynamic level. The tone of a trumpet, for example, is "brighter" when it is played *fortissimo* than when it is played *piano* because more high-frequency components are excited when the instrument is blown harder. Our listening experience with this property of a trumpet allows us to distinguish between, say, the sound of a trumpet played softly near the listener and that of a trumpet played loudly but farther away, even though the total intensity of the two sounds might be equal. In other words, we simply cannot turn the sound of a softly played trumpet into that of a loudly played one by turning up a volume control, that merely increases the intensity of the sound. Even assuming a

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[8] Frequency components separated by less than a critical band interact to produce a "rough" or "beating" sound. At frequencies above about 500 Hz, the size of the critical band is between a major second and a minor third. Below 500 Hz, the critical band becomes progressively larger.

[9] It is important to keep in mind that a *frequency component* is essentially a sinusoidal vibration pattern. The loudness of complex tones such as those of musical instruments will be determined by the interactions of all of the frequency components in both tones.

[10] This effect is attributed primarily to masking of the softer components by louder ones.

constant distance between sound source and listener, we find that intensity is but one factor in determining the overall sense of musical dynamic level.

Musical imagination tends to work in terms of desired interpretations that a musician wishes to impart to the listener on a cognitive level. To produce a desired effect with a computer, we must be acutely aware that the end effect of a synthetic sound will be determined first by how it is perceived and that it will be perceived according to what is physically there. The computer allows us to manipulate the physical properties of the generated sound with great precision, but it is the responsibility of the musician to understand the mapping of these properties through the perceptual and cognitive processes of the listener.

THE DISCIPLINARY CONTEXT OF COMPUTER MUSIC

Most academic disciplines are disciplines of thought. They exist in order to define a "correct" (or at least useful) view of some subset of human knowledge. Computer music, however, is strongly interdisciplinary. In computer music, therefore, a "correct" view is one that does justice to several points of view simultaneously. An awareness of these points of view is important not so much because ignorance of any one of them makes it impossible to do anything but because what may be done will eventually be limited by that lack of awareness. A great deal has been discovered in different places, and in using the computer to make music, artists are obliged to master as much of this medium of expression as possible.

What are these "several" points of view? In computer music, they start with an awareness of the principles of music (see Figure 1-5). Music is a complicated and very technical subject, the study of which involves the acquisition of as much skill as knowledge. Development of skill generally requires much practice, making it take a long time to learn about music. Practically every facet of music comes into play in the act of its creation. A lack of knowledge of the history of music would give a serious composer certain distinct liabilities, for example. Similarly, a lack of knowledge of music theory, compositional principles, or performance practice would eventually place a limitation on the music produced by any individual.

In programming the computer to make music, we must deal with what philosophers would call objective knowledge about music. While the design of the musical result may include purely subjective components, the accurate reflection of these components in objective choices determines the quality of the resulting musical work. Some fluency in the realm of what is objectively known about music is therefore necessary.

Sound, for instance, is the objective manifestation of music. A great deal is known about sound in general, though perhaps not as much as musicians might like. The science of acoustics—a branch of physics—deals systematically with the objective properties of sound.

Because music is an art produced by humans for the appreciation of other humans, we must also deal with the perceptual qualities of sound, which are in the

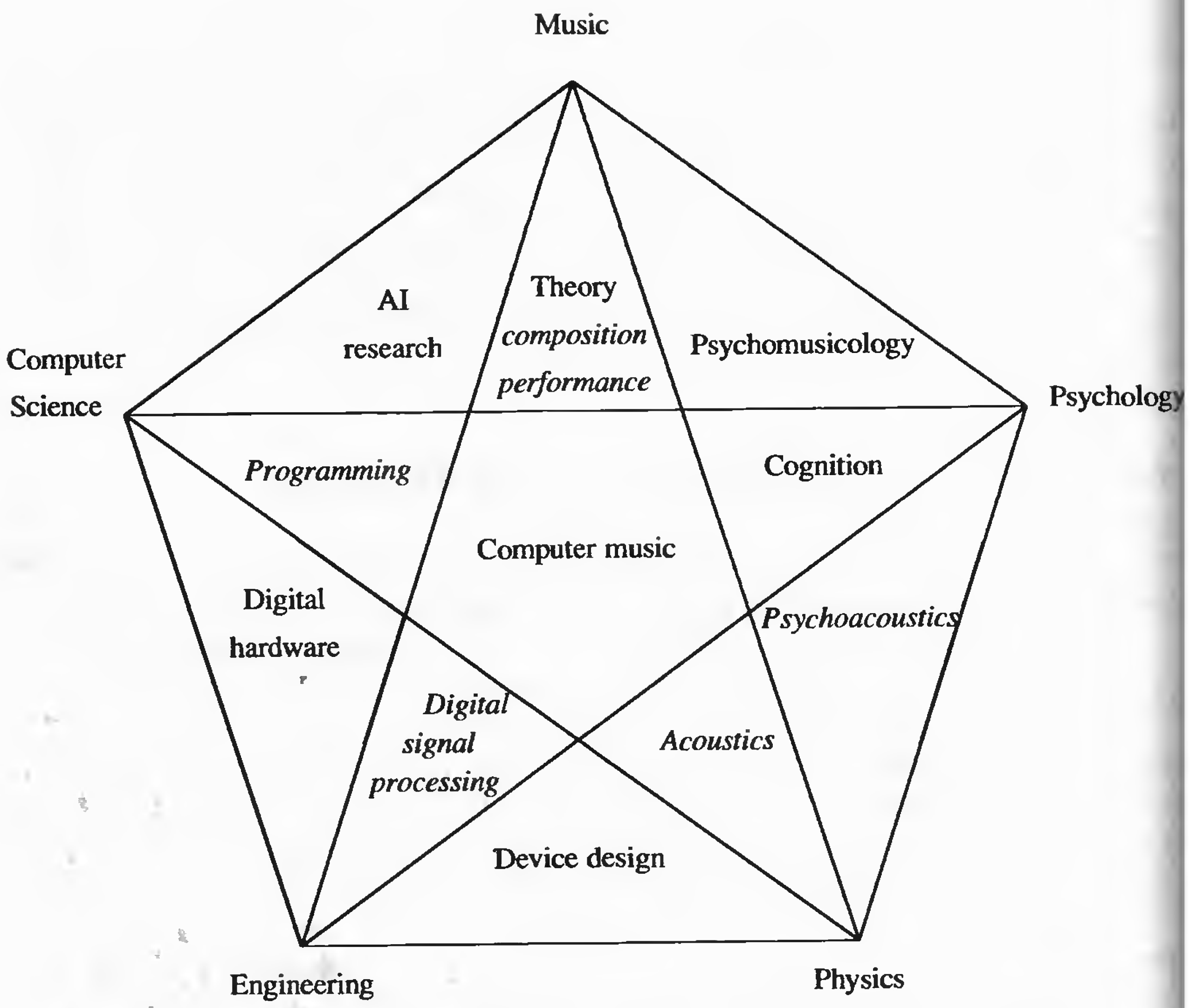

Figure 1-5 Disciplinary context of computer music (essential subdisciplines are shown in *italics*).

purview of psychoacoustics. Many of the most profound problems of computer music lie in the development of new understandings relating what we perceive to what is there. Quite often we are after a particular musical effect, but the properties of the sound are all we can manipulate. Understanding the relation between the objective and subjective properties of sound are at the heart of computer music.

In addition to recognizing the objective properties of sound, the computer requires instructions about how to manipulate it. This is in the realm of digital signal processing, a branch of electrical engineering. Without some knowledge of digital signal processing techniques, all the knowledge of acoustics in the world would not allow us to manipulate sounds with a computer.

Finally, all of the knowledge and skill brought to bear on the problems of computer music must eventually be realized in the form of one or more computer programs. Computer programming is a branch of the more general field of computer science, and it is becoming an increasingly sophisticated art in itself. If the programs required for music production were simple, a rudimentary knowledge of programming would probably suffice in most cases. But the problems of generating music often stretch the capabilities of computers to their limits, making programming skill a determining factor in the viability of many musical plans.

In this treatment of computer music, therefore, we will concentrate on elements that have proved to be useful in the analysis, modification, and synthesis of musical sounds and structures. While much less is known in these areas than we as musicians might like, a great deal is known, though much of it is couched in terms that are not traditionally musical. To be on the same level with the phenomenon of computer music, we shall need the resolve to go considerably beyond musical tradition, into the realms of digital signal processing, acoustics, psychoacoustics, and nontraditional musical structures, all of which is unified by the rich cross-fertilization of music and computers.

9 PREREQUISITES

As we have seen, computer music is so strongly interdisciplinary that it would be virtually impossible to describe it in any comprehensive way ''from scratch'' in a single volume. It is therefore important to make any assumptions about background explicit from the outset.

First and foremost, you must have at least a rudimentary knowledge of musical composition and performance. This includes a familiarity with music notation and the essentials of music theory, including harmony, counterpoint, and orchestration, possibly extending to contemporary serial, aleatoric, and notational techniques.

Second, you must have a rudimentary knowledge of musical acoustics and psychoacoustics. Fortunately, such basic information about sound and its perception is obtainable from a number of well-written and readily available textbooks. Unfortunately, most courses of music study do not include acoustics or psychoacoustics, even though it is hard to imagine anything more useful to a practicing musician than a basic understanding of sound and its perception.

Third, you must know at least the fundamentals of computer programming. All programming examples in this book will be written in the C language, which should be readily understandable if you have programming experience in any structured ''algorithmic'' language such as Pascal, PL/I, Ratfor (structured FORTRAN), or Algol.

Finally, a word about mathematics. To make the information in this book as widely accessible as possible, mathematical discussions will generally avoid calculus. Only standard high school–level algebra and trigonometry are needed to understand most of the mathematical techniques used in this book. It will sometimes be necessary, however, to define and use mathematical terminology and techniques that go beyond those normally encountered in high school math. Fortunately, there are many excellent review books written on the subject of mathematics that you may find useful from time to time.

With a basic knowledge of music, acoustics, programming, and elementary mathematics, you should find the concepts and techniques of computer music readily accessible. Even dubious preparation in any one of these areas should not hinder you from making good progress, provided you keep a good reference handy.

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