Curtis Roads

the computer music tutorial

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with John Strawn, Curtis Abbott, John Gordon, and Philip Greenspun

The Computer Music Tutorial

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Foreword: New Music and Science

With the use of computers and digital devices, the processes of music composition and its production have become intertwined with the scientific and technical resources of society to a greater extent than ever before. Through extensive application of computers in the generation and processing of sound and the composition of music from levels of the microformal to the macroformal, composers, from creative necessity, have provoked a robust interdependence between domains of scientific and musical thought. Not only have science and technology enriched contemporary music, but the converse is also true: problems of particular musical importance in some cases suggest or pose directly problems of scientific and technological importance, as well. Each having their own motivations, music and science depend on one another and in so doing define a unique relationship to their mutual benefit.

The use of technology in music is not new; however, it has reached a new level of pertinence with the rapid development of computer systems. Modern computer systems encompass concepts that extend far beyond those that are intrinsic to the physical machines themselves. One of the distinctive attributes of computing is programmability and hence programming languages. High-level programming languages, representing centuries of thought about thinking, are the means by which computers become accessible to diverse disciplines.

Programming involves mental processes and rigorous attention to detail not unlike those involved in composition. Thus, it is not surprising that composers were the first artists to make substantive use of computers. There were compelling reasons to integrate some essential scientific knowledge and concepts into the musical consciousness and to gain competence in areas which are seemingly foreign to music. Two reasons were (and are) particularly compelling: (1) the generality of sound synthesis by computer, and (2) the power of programming in relation to the musical structure and the process of composition.

Sound Synthesis

Although the traditional musical instruments constitute a rich sound space indeed, it has been many decades since composers' imaginations have conjured up sounds based on the interpolation and extrapolation of those found in nature but which are not realizable with acoustical or analog electronic instruments. A loudspeaker controlled by a computer is the most general synthesis medium in existence. Any sound, from the simplest to the most complex, that can be produced through a loudspeaker can be synthesized with this medium. This generality of computer synthesis implies an extraordinarily larger sound space, which has an obvious attraction to composers. This is because computer sound synthesis is the bridge between that which can be imagined and that which can be heard.

With the elimination of constraints imposed by the medium on sound production, there nonetheless remains an enormous barrier which the composer must overcome in order to make use of this potential. That barrier is one of lack of knowledge—knowledge that is required for the composer to be able to effectively instruct the computer in the synthesis process. To some extent this technical knowledge relates to computers; this is rather easily acquired. But it mostly has to do with the physical description and perceptual correlates of sound. Curiously, the knowledge required does not exist, for the most part, in those areas of scientific inquiry where one would most expect to find it, that is, physical acoustics and psychobiology, for these disciplines often provide either inexact or no data at those levels of detail with which a composer is ultimately most concerned. In the past, scientific data and conclusions were used to try to replicate natural sounds as a way of gaining information about sound in general. Musicians and musician-scientists were quick to point out that most of the conclusions and data were insufficient. The synthesis of sounds which approach in aural complexity the simplest natural sound demands detailed knowledge about the temporal evolution of the various components of the sound.

Physics, psychology, computer science, and mathematics have, however, provided powerful tools and concepts. When these concepts are integrated with musical knowledge and aural sensitivity, they allow musicians, scientists, and technicians, working together, to carve out new concepts and physical and psychophysical descriptions of sound at levels of detail that are of use to the composer in meeting the exacting requirements of the ear and imagination.

As this book shows, some results have emerged: There is a much deeper understanding of timbre, and composers have a much richer sound palette with which to work; new efficient synthesis techniques have been discovered and developed that are based upon modeling the perceptual attributes of sound rather than the physical attributes; powerful programs have been developed for the purposes of editing and mixing synthesized and/or digitally recorded sound; experiments in perceptual fusion have led to novel and musically useful research in sound source identification and auditory images; finally, special purpose computer-synthesizers are being designed and built. These real-time performance systems incorporate many advances in knowledge and technique.

Programming and Composition

Because one of the fundamental assumptions in designing a computer programming language is generality, the range of practical applications of any given high-level language is enormous and obviously includes music. Programs have been written in a variety of programming languages for various musical purposes. Those that have been most useful and with which composers have gained the most experience are programs for the synthesis and processing of sound and programs that translate musical specifications of a piece of music into physical specifications required by the synthesis program.

The gaining of some competence at programming can be rewarding to a composer as it is the key to a general understanding of computer systems. Although systems are composed of programs of great complexity and written using techniques not easily learned by nonspecialists, programming ability enables the composer to understand the overall workings of a system to the extent required for its effective use. Programming ability also gives the composer a certain independence at those levels of computing where independence is most desirable—synthesis. Similar to the case in traditional orchestration, the choices made in the synthesis of tones, having to do with timbre and microarticulation, are often highly subjective. The process is greatly enhanced by the ability of the composer to alter synthesis algorithms freely.

The programming of musical structure is another opportunity which programming competence can provide. To the extent that compositional processes can be formulated in a more or less precise manner they may be implemented in the form of a program. A musical structure that is based upon some iterative process, for example, might be appropriately realized by means of programming.

But there is a less tangible effect of programming competence which results from the contact of the composer with the concepts of a programming language. While the function a program is to perform can influence the choice of language in which the program is written, it is also true that a programming language can influence the conception of a program's function. In a more general sense, programming concepts can suggest functions that might not occur to one outside of the context of programming. This is of signal importance in music composition, since the integration of programming concepts into the musical imagination can extend the boundaries of the imagination itself. That is, the language is not simply a tool with which some preconceived task or function can be accomplished; it is an extensive basis of structure with which the imagination can interact, as well.

Although computer synthesis of sound involves physical and psychophysical concepts derived from the analysis of natural sounds, when joined with higher-level programming of musical structure the implications extend far beyond timbre. Unlike the condition that exists in composition for traditional instruments where the relation of vibrational modes of an instrument is largely beyond compositional influence, computer synthesis allows for the composition of music's microstructure.

In the context of computing, then, the microstructure of music is not necessarily of predetermined form—associated with a specific articulation of a particular instrument. Rather, it can be subjected to the same thought processes and be as freely determined in the imagination of the composer as every other aspect of the work.

John Chowning

Preface

Music changes: new forms appear in infinite variety, and reinterpretations infuse freshness into old genres. Waves of musical cultures overlap, diffusing new stylistic resonances. Techniques for playing and composing music meander with these waves. Bound with the incessant redevelopment in music-making is an ongoing evolution in music technology. For every music there is a family of instruments, so that today we have hundreds of instruments to choose from, even if we restrict ourselves to the acoustic ones.

In the twentieth century, electronics turned the stream of instrument design into a boiling rapids. Electrification transformed the guitar, bass, piano, organ, and drum (machine) into the folk instruments of industrial society. Analog synthesizers expanded the musical sound palette and launched a round of experimentation with sound materials. But analog synthesizers were limited by a lack of programmability, precision, memory, and intelligence. By virtue of these capabilities, the digital computer provides an expanded set of brushes and implements for manipulating sound color. It can listen, analyze, and respond to musical gestures in sophisticated ways. It lets musicians edit music or compose according to logical rules and print the results in music notation. It can teach interactively and demonstrate all aspects of music with sound and images. New musical applications continue to spin out of computer music research.

In the wake of ongoing change, musicians confront the challenge of understanding the possibilities of the medium and keeping up with new developments. *The Computer Music Tutorial* addresses the need for a standard and comprehensive text of basic information on the theory and practice of computer music. As a complement to the reference volumes *Foundations of Computer Music* (MIT Press, 1985) and *The Music Machine* (MIT Press, 1989), this book provides the essential background necessary for advanced exploration of the computer music field. While *Foundations of Computer Music* and *The Music Machine* are anthologies, this textbook contains all new material directed toward teaching purposes.

Intended Audience

The intended audience for this book is not only music students but also engineers and scientists seeking an orientation to computer music. Many sections of this volume open technical "black boxes," revealing the inner workings of software and hardware mechanisms. Why is technical information relevant to the musician? Our goal is not to turn musicians into engineers but to make them better informed and more skillful users of music technology. Technically naive musicians sometimes have unduly narrow concepts of the possibilities of this rapidly evolving medium; they may import conceptual limitations of bygone epochs into a domain where such restrictions no longer apply. For want of basic information, they may waste time dabbling, not knowing how to translate intuitions into practical results. Thus one aim of this book is to impart a sense of independence to the many musicians who will eventually set up and manage a home or institutional computer music studio.

For some musicians, the descriptions herein will serve as an introduction to specialized technical study. A few will push the field forward with new technical advances. This should not surprise anyone who has followed the evolution of this field. History shows time and again that some of the most significant advances in music technology have been conceived by technically informed musicians.

Interdisciplinary Spirit

The knowledge base of computer music draws from composition, acoustics, psychoacoustics, physics, signal processing, synthesis, composition, performance, computer science, and electrical engineering. Thus, a well-rounded pedagogy in computer music must reflect an interdisciplinary spirit. In this book, musical applications motivate the presentation of technical concepts, and the discussion of technical procedures is interspersed with commentary on their musical significance.

Heritage

One goal of our work has been to convey an awareness of the heritage of computer music. Overview and background sections place the current picture into historical context. Myriad references to the literature point to sources for further study and also highlight the pioneers behind the concepts.

Concepts and Terms

Every music device and software package uses a different set of protocols—terminology, notation system, command syntax, button layout, and so on. These differing protocols are built on the fundamental concepts explained in this volume. Given the myriad incompatibilities and the constantly changing technical environment, it seems more appropriate for a book to teach fundamental concepts than to spell out the idiosyncracies of a specific language, software application, or synthesizer. Hence, this volume is not intended to teach the reader how to operate a specific device or software package—that is the goal of the documentation supplied with each system. But it will make this kind of learning much easier.

Use of This Book in Teaching

The Computer Music Tutorial has been written as a general textbook, aimed at presenting a balanced view of the international scene. It is designed to serve as a core text and should be easily adaptable to a variety of teaching situations. In the ideal, this book should be assigned as a reader in conjunction with a studio environment where students have ample time to try out the various ideas within. Every studio favors particular tools (computers, software, synthesizers, etc.), so the manuals for those tools, along with studio-based practical instruction, can round out the educational equation.

Roadmap

The Computer Music Tutorial is apportioned into seven parts, each of which contains several chapters. Part I, Fundamental Concepts, serves as an introduction to digital audio and computer technology. Familiarity with the material in these chapters will be helpful in understanding the rest of this volume.

The second part focuses on digital sound synthesis. Chapters 3 through 8 cover the major synthesis methods, including both experimental and commercially available methods.

Part III, Mixing and Signal Processing, contains four chapters that demystify these sometimes arcane subjects, including sound mixing, filtering, delay effects, reverberation, and spatial manipulation.

Analysis of sound, the subject of part IV, is on the ascendency, being key to many musical applications such as sound transformation, interactive performance, and music transcription. Chapters 12 and 13 cover the analysis of pitch, rhythm, and spectrum by computer.

Part V addresses the important subject of the musician's interface for computer music systems. The physical devices manipulated by a performer are the subject of chapter 14, while chapter 15 deals with the software that interprets a performer's gestures. Chapter 16 is a survey of music editing systems. Music languages are the subject of chapter 17. The last two chapters in part V introduce the universe of algorithmic composition methods and representations.

Part VI opens the lid of computer music systems, beginning with an examination of the internals of digital signal processors in chapter 20. Chapter 21 discusses the popular MIDI interface protocol, while chapter 22 looks at interconnections between computers, input devices, and digital signal processing hardware.

The seventh part contains a single chapter on psychoacoustics by John Gordon, which deals with the instrument of listening—human perception. Knowledge of the basic concepts in psychoacoustics can help in several aspects of computer music, including sound design, mixing, and interpreting the output of signal analysis programs.

The final part of the book is a technical appendix introducing readers to the history, mathematics, and overall design of Fourier analysis, in particular the fast Fourier transform—a ubiquitous tool in computer music systems.

Composition

Notwithstanding the broad scope of this book, it was impossible to compress the art of composition into a single part. Instead, readers will find many citations to composers and musical practices interwoven with technical discussions. Chapters 18 and 19 present the technical principles behind algorithmic composition, but this is only one facet of a vast—indeed openended—discipline, and is not necessarily meant to typify computer music composition as a whole.

We have surveyed composition practices in other publications. *Composers and the Computer* focuses on several musicians (Roads1985a). During my tenure as editor of *Computer Music Journal*, we published many reviews of compositions, interviews with, and articles by composers. These include a "Symposium on Composition," with fourteen composers partipating (Roads 1986a), and a special issue on composition, *Computer Music Journal* 5(4) 1981. Some of these articles were reprinted in a widely available text, *The Music Machine* (MIT Press 1989). Issue 11(1) 1987 featured microtonality in computer music composition. Many other periodicals and books contain informative articles on compositional issues in electronic and computer music.

References and Index

In a tutorial volume that covers many topics, it is essential to supply pointers for further study. This book contains extensive citations and a reference list of more than 1300 entries compiled at the back of the volume. As a further service to readers, we have invested much time to ensure that both the name and subject indexes are comprehensive.

Mathematics and Coding Style

Since this *Tutorial* is addressed primarily to a musical audience, we chose to present technical ideas in an informal style. The book uses as little mathematical notation as possible. It keeps code examples brief. When mathematical notation is needed, it is presented with operators, precedence relations, and groupings specified explicitly for readability. This is important because the idioms of traditional mathematical notation are sometimes cryptic at first glance, or incomplete as algorithmic descriptions. For the same reasons, the book usually uses long variable names instead of the single-character variables favored in proofs. With the exception of a few simple Lisp examples, code examples are presented in a Pascal-like pseudocode for readibility.

Appendix A presents advanced material and denser mathematical formulas. For this reason we fall back on traditional mathematical notation therein.

Corrections and Comments Invited

In the first edition of a large book covering a new field, there will inevitably be errors. We welcome corrections and comments, and we are always seeking further historical information. Please address your comments to the author in care of The MIT Press, 55 Hayward Street, Cambridge, Massachusetts 02142.

Acknowledgments

This book was written over a period of many years. I wrote the first draft from 1980 to 1986, while serving as Research Associate in computer music at the Massachusetts Institute of Technology and Editor of *Computer Music Journal* for The MIT Press. I am grateful to many friends for their assistance during the period of revisions that followed.

Major sections of part III (Mixing and Signal Processing) and part IV (Sound Analysis) were added during a 1988 stay as Visiting Professor in the Department of Physics at the Università di Napoli Federico II, thanks to an invitation by Professor Aldo Piccialli. I am deeply grateful to Professor Piccialli for his detailed comments on chapter 13 (Spectrum Analysis) and appendix A (Fourier Analysis), and for his generous counsel on the theory of signal processing.

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During spare moments I worked on part V (The Musician's Interface) in Tokyo at the Center for Computer Music and Music Technology, Kunitachi College of Music, in 1991, thanks to the center's director Cornelia Colyer, Kunitachi chairman Bin Ebisawa, and a commission for a composition from the Japan Ministry of Culture. I presented the first courses based on the completed text in 1993 and 1994 at Les Ateliers UPIC, thanks to Gerard Pape and Iannis Xenakis, and the Music Department of the University of Paris VIII, thanks to Professor Horacio Vaggione.

John Strawn, formerly my editorial colleague at *Computer Music Journal*, contributed substantially to this project for several years. In between his duties as a doctoral student at Stanford University, he wrote parts of chapters 1 and 3. Later, he reviewed drafts of most chapters with characteristic thoroughness. Throughout this marathon effort, John was consulted on myriad details via electronic mail. I am grateful to him for sharing his wide musical and technical knowledge and sharp wit.

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