Inside Computer Music
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In memory of Jonathan Harvey
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The generosity of all these people and organisations has enabled us to bring together a wide range of creative and technical information in our investigation into how these factors are combined in the realization of innovative musical works.
About the companion website

www.oup.com/us/insidecomputermusic

Oxford has created a website to accompany *Inside Computer Music*. Material that cannot be made available in a book, namely demonstration videos for each chapter and links to the software, are provided here. The reader is encouraged to consult this resource in conjunction with the book. Examples available online are indicated in the text with Oxford’s symbol ☞.
Technology and Creativity in Computer Music

Combining text and software to explore computer music from the inside

This publication (the text and the software) aims to explore the relationship between new technical innovations in computer technology for music and the creative practice of composers employing these new techniques. It asks the following questions: Does the new technology lead to new sounds and new ways of structuring music, and if so how? What are the creative options, sonic and structural, presented by new software and hardware? How can these be manipulated and shaped to form music? How have particular composers developed successful working methods in using this technology?

To answer such questions, a set of case studies has been examined in depth, involving specific works in which composers have adopted new techniques, whether developed by themselves or by others. Each of these works has been researched from a number of different perspectives: the technical and musical background, the technology employed in the particular work, and, through music analysis, the musical outcome. Innovative approaches have been employed both in undertaking and presenting this research. On the one hand, it has been important to find appropriate ways of presenting the musical potential
of what are often highly technical processes. On the other hand, it has been necessary to find ways of analyzing music that often evades even the most basic fundamentals of traditional music analysis: notes, harmonies, or instruments.

The approach taken has been to adopt, and very significantly enhance, techniques of interactive aural analysis. In essence this approach closely links text and interactive software. The software allows users to engage with emulations of the techniques used by the composers. In this way, readers can learn about the technology and its musical potential for themselves, and perhaps gain some insight into the issues and challenges faced by the composers as they worked. Software also enables the musical analyses to be conducted in the medium of sound itself. This is especially important for musics, such as those of our case studies, where traditional notation and verbal analytical terminology are not ideally suited to the sounds and structures of the works. Software also makes possible the incorporation of video recordings of interviews with the composers and/or technical innovators involved in a composition, sometimes illustrating their ideas with live demonstrations. Again, this is something that could not be achieved simply on paper.

Each of the nine case studies has its own dedicated software application, addressing the musical materials and structures, compositional processes, and technologies with interactive presentations that are inevitably specific to the composer and work being studied. However, these nine applications have been developed with a unified design and common overall architecture. For each case, the interactive aural presentations are either “explorers” or videos organized around specific aspects or topics, and the succession of interactive explorers is globally ordered as follows: the first explorer is always a representation of the work as a whole, enabling users to navigate aurally the entire musical structure, explore the categories of materials or processes, and get familiar with the significant components of the piece. Then, the examples that follow present simple instances of the technologies used by the composer, introducing their fundamental properties and sound potential. The subsequent examples then grow in complexity, inviting the reader to learn incrementally, from simple principles to their actual implementation in the context of the studied work. Where relevant, some interactive analytical charts are also provided, as well as emulations of the systems used at the time of composition.

It is important to underline the fact that, even though the focus of this publication is on the role of technology in musical creation, the software applications are meant to be entirely accessible, and any reader can easily engage with these resources. No particular technological knowledge or skills are needed to explore the nine case studies interactively.

Demonstration Video 0.1 is an introduction to the accompanying software, showing its general architecture, modes of use and navigation, and examples of interactive
Technical innovation is therefore employed in order to investigate technical innovation, and hopefully to demonstrate something of the creativity this facilitates in the works of the composers studied. Text nonetheless plays a crucial role in articulating ideas, and the integration of text and software is vital. In this book, therefore, there are frequent links to video demonstrations of the software relevant to a particular point being made in the text, as with Demonstration Video 0.1. These short videos act both as illustrations of such points and also as mini-tutorials to guide readers in how to use the software. Although the videos will provide some insight into the potential of software, to gain the most out of it, and to learn in greater depth, it is important to download the software and use it interactively. The learning then becomes open-ended: in many cases additional material is provided relating to the work, which it was not possible to incorporate fully into the textual discussions. So readers will be able, if they wish, to extend their research into particular case studies beyond what is presented here.

The pursuit of new perspectives in the analysis of electronic and computer music

The generic descriptor “electronic music” embraces an abundance of sound production and manipulation techniques, explored in an equally extensive range of creative contexts. Whereas acoustic music is associated with general typologies that are well understood by those who take an interest in the classical repertory, such as orchestral music, chamber music, folk music, opera, or jazz, the same or even a suitably equivalent sense of identity cannot be assumed in the case of music that makes use of the electronic medium. The evolution of rock and popular music provides a good example of the problems that are often encountered in such a context. For many listeners it is the more immediate sonic characteristics of the associated works that determine the limits of their engagement with the underlying technical and musical processes. As a result, many of the contributing components in both contexts that have led to specific classifications, such as electronic dance, industrial, techno, hip-hop, and ambient music, are only superficially understood by the wider public.

The implications of this dichotomy are considerable, not least for those who wish to gain an informed understanding of electronic music, and it is thus especially important to introduce the reader to the key issues that have shaped and influenced the research project that led to the production of this book, as well as the accompanying software and related audiovisual materials.
Other analytical approaches to this repertoire can be found in *Electroacoustic Music: Analytical Perspectives*, edited by Thomas Licata (1982); *Analytical Methods of Electroacoustic Music*, edited by Mary Simoni (2006); *Expanding the Horizon of Electroacoustic Music Analysis*, edited by Simon Emmerson and Leigh Landy (2016); and *Between the Tracks: Musicians on Selected Electronic Music*, edited by Miller Puckette and Kerry Hagan (2020). For those readers who wish to study the medium in a wider context, attention is drawn to three books also published by Oxford University Press, which have a useful role as companion texts: *Electronic and Computer Music* by Peter Manning (2013); *The Oxford Handbook of Computer Music*, edited by Roger Dean (2009); and *Composing Electronic Music: A New Aesthetic* by Curtis Roads (2015).

There are some important differences between the genres of music that have explored the possibilities of purely acoustic resources over the years and those that have been based on sounds produced by an electronic means. While the development of both Western and non-Western music has taken place over many centuries, the evolution of electronic music has occupied a much shorter time span. Although speculative predictions on how sound might be manipulated in a future domain date back as far as those made by Francis Bacon in his visionary work *New Atlantis* (1626), for all intents and purposes the birth of the medium extends back no further than the pioneering work of Thomas Edison on the practical uses of electricity during the latter part of the nineteenth century, preparing the ground for the introduction of the thermionic valve in 1906 and all that was to follow in terms of the development of electronic resources for sound production and audio signal processing.

Progress over the subsequent decades leading up to the Second World War was limited in the first instance to a diverse series of individual initiatives that engaged with the technical and musical considerations necessary to underpin what was essentially a journey into entirely uncharted territory. In a technical context, one of the more notable outcomes was a succession of electronic musical instruments conceived as additions to the existing repertory of acoustic musical instruments. These included the Theremin (1924), the Ondes Martenot (1928), and the Trautonium (1930). The Hammond organ (1935) was an exception to this trend, being specifically designed as a direct replacement for the pipe organ, and in due course as an alternative to the conventional acoustic piano. Crossing boundaries from the conventional to the unconventional in terms of electronically produced sound, however, required the evolution of musical aesthetics that embraced new creative horizons, and here the diversity of pioneering ventures is quite remarkable, ranging from the revolutionary ideas of the Futurists and Ferruccio Busoni to those of Edgard Varèse and John Cage. The intervention of the war interrupted these preparatory steps toward establishing such a new medium of musical expression. However, the rapid advances in communication technologies during this time were to prove of material practical significance for future developments.
By the termination of the war in 1945, the stage had been set for a series of important initiatives both in Europe and the United States that finally established the development of a composing and performing medium that was to become generally known as electronic music. These initiatives were based in the first instance on analog technologies, ranging from individual hardware devices that could be used to generate and manipulate audio signals, such as laboratory oscillators and filters, to facilities for mixing and recording sound materials via the medium of magnetic tape. Although in Europe these developments were primarily concentrated in studios funded by national broadcasting corporations, notably in Paris, Cologne, and Milan, a somewhat more diffuse series of both collective and university-based initiatives was to emerge in the United States. During the 1950s the scope and level of activities continued to gather pace, not only in Europe and the United States, but also further afield, notably in Japan, and by the end of the decade the general public was starting to become aware of the world of electronic sounds, embracing applications ranging from simple sound effects to complete artworks. Access to suitable facilities for aspiring composers, however, remained for the most part restricted to those fortunate enough to gain access to an established electronic studio.

This emphasis on exclusivity was to change during the mid-1960s with the production of commercially produced analog synthesizers from manufacturers such as Moog, Buchla, ARP, and EMS (London). This development made suitable facilities available to a much wider spectrum of creative artists, and also signaled the start of a major revolution in its own right concerning the use of electronics as a resource for a rapidly expanding world of rock and pop music. As the medium of electronic music continued to develop during the 1970s, its creative possibilities were explored with increasing intensity and diversity. The positive trajectory of the associated technical developments continued well into the early 1980s, changing direction as the decade advanced into one of progressive decline as alternative technologies based on digital engineering became more generally available. By the end of the 1990s the design and manufacture of analog equipment for electronic music had all but ceased, and gradually the term “computer music” came into general use.

The implications of this material change of circumstances were not immediately grasped. Many practitioners assumed that the new era of digital engineering would simply subsume and enhance the key features of the older technologies, thus ensuring continuity with former ways of working with electronic resources. To a certain extent such aspirations were indeed possible. However, the digital domain soon opened up new avenues for exploring the creative possibilities of the medium, focusing attention away from preserving the unique practical ways of working with analog equipment. Obsolescence was thus fast becoming a significant consideration.

During the early 2000s other concerns arising from the passage of time were to surface. Whereas formerly a significant proportion of those who had
contributed to the development of the medium since the Second World War could provide personal and highly informative insights into its evolution, these direct lines of communication were starting to diminish as, one by one, the individuals concerned passed away. A similar situation was to materialize in terms of access to the legacy of completed works. Here there are some important differences to be noted between electronic and acoustic compositions. The conventionally notated scores associated with the latter repertory provide definitive reference points, both for a detailed study of each work and also for the production of subsequent performances and recordings at any point into the future. In addition, the physical nature of the score ensures a significant degree of sustainability, unaffected by the passage of time. Recordings of electronic music, however, are problematic in a number of respects. Early electronic music works created in studios were recorded on magnetic tape, with commercial works released on vinyl. Over the years, many of the original master tapes have degraded to the point where they can no longer be played. As a result, the works concerned are lost for eternity. Although the advent of the compact disc in 1982 signaled the start of a digital recording revolution that was ultimately to transform the world of music production, distribution, and preservation, a significant number of electronic composers continued to master their works on magnetic tape. The key to a wholesale move to digital recording lay in the development of recording facilities for the personal computer, but these only reached maturity after the turn of the century.

In the current environment of highly sophisticated digital technologies, it is thus important to recognize the significance of three legacy issues that arise from the above observations: (1) how to secure continuing access to the repertory of works composed over the years, (2) how to secure and sustain access to the various technologies that have been used in their production, and (3) wherever possible to enhance our understanding of these works by directly interrogating both the composers concerned and those responsible for the design of the resources they used to create their works. In many respects the latter objective is the most elusive, for self-evident reasons. However, the potential insights arising from such engagements provide powerful incentives for such inquiries.

Much has been written on electronic music from a variety of perspectives, from the early pioneering era to the present day, and it is important to appreciate that the resulting production of books, articles, and allied materials have collectively made important contributions to our knowledge and understanding of the medium as it has developed over the years. Nonetheless, for the reasons discussed earlier, there is some way to go before such lines of inquiry achieve their full potential. Particular attention has been paid in more recent years to the practical techniques that can be used to study the key features of individual works, and significant progress has been made in terms of developing different approaches to sonic analysis, ranging from feature analysis
using subjective criteria applied through listening to analysis of the spectral content using software for digital signal processing. There is, however, a further question that has to be addressed: What is the scope and nature of information being sought in such contexts, and why and to what extent will the outcomes assist our understanding of the work concerned? The issues arising in this context are necessarily complex and embrace a multitude of different perspectives and objectives. These circumstances make it especially important for the authors of this book and the accompanying materials to introduce the reader to the specific rationale that underpins the choice of composer and the associated detailed study of an associated work in each of the nine chapters that follow.

A useful starting point in this context concerns the reasons why the authors were motivated to embark upon this program of musical and technical research, consolidated in the arguments put forward to secure funding from the UK Arts and Humanities Research Council. A fundamental objective was the development of suitable ways and means of addressing key aspects of the legacy issues identified earlier, and in so doing provide new insights into both the creative and technical characteristics of the medium of electronic music. The following questions were identified as key elements of the proposed methodology:

- How far has technology had an important impact on the musical creativity of electronic music composers?
- How do the resources of music technology and the creative processes of composition interact in individual works, and what is the musical significance of this interaction?
- How far is the use of technology here guided by particular aesthetic/creative principles?
- How is the musical structure formed in these works, and how far and in what ways has the technology enabled new creative possibilities in terms of shaping sounds and/or forming musical structures?
- How does a specific work relate to the composer’s practice more generally, and what is its contribution, in the broader context, to the development of electronic music?

In order to embark on such far-reaching investigations, it was first necessary to identify a group of works upon which to base a suitably focused program of research. The criteria used in this context need some explanation, since the choices made have of necessity materially influenced the scope and nature of the perspectives that have emerged. A primary decision made at the outset was to focus specifically on works that have contributed to the evolution of computer music as a domain in its own right—hence the title of the book. As noted earlier, the transition from analog to digital technologies has materially transformed the creative environment for composing electronic music, with the consequences embracing both art and popular genres. Furthermore, although
the full impact of this step change was to take a number of years to come to fruition, the pioneering phase of computer music dating back to the late 1950s established the key methods of digitally generating and processing sounds that are widely employed today. This strategy facilitated a further set of questions based on issues that hitherto have only been partially explored:

- Can software, with interactive aural examples, articulate technical issues in a more musically meaningful way for a nontechnical audience?
- Can the discussion of music that exists primarily as sound and is essentially temporal and transitory in nature be facilitated by software that incorporates interactive manipulation of sound examples?
- Can software provide a means of demonstrating the interrelation of the musical and the technical in a manner that is more meaningful to an extended range of end users?

**Nine case studies from the history of computer music**

The starting point for this journey is the birth of the digital computer—a fascinating study in its own right. In the same way that World War II resulted in a major stimulus for the technologies necessary to underpin the development of analog electronic music, the increasing demands for facilities capable of processing large quantities of information data spurred pioneers to investigate the possibilities of developing ways and means of converting the techniques of early mechanical calculators into an electronic, and in due course fully programmable, environment.

Parallel initiatives establishing the design principles associated with the development of digital computers gathered pace during the early postwar years in a number of countries, notably the United States, the United Kingdom, and Australia, but the key to their future lay in attracting the interest of commercial manufacturers. Although credit here is due to Remington Rand for its pioneering 409 model, launched in 1949, it was the entry of IBM into the field in 1953 that marks the start of developments that were to prove of lasting significance to the evolution of computer music, starting with the pioneering work of Max Mathews and his associates at Bell Telephone Laboratories (aka Bell Labs) from the mid-1950s onward. Chapter 1, focusing on the work of John Chowning, and in particular the composition of his work *Stria* (1977), using software originally developed by Mathews, provides an insight into this early phase of computer music, based in the first instance on the resources provided by large mainframe computers. Chowning’s contributions to the development of the medium have been considerable, not least in the context of his pioneering
work with frequency modulation (FM) synthesis, a powerful and versatile method of generating sound material for computer music that is still widely used today.

One notable distinction between the early years of computer music and concurrent developments in electronic music based on analog technologies was the exclusivity of the former domain, limited to a handful of pioneers able to gain access to institutional computers. Allocations for processing time were at a premium, and this further restricted the opportunities for aspiring composers and researchers, both at Bell Labs and elsewhere. The first tentative steps in the latter context were taken by the universities of Princeton and Columbia during the early 1960s. By the early 1970s, developments started to gather pace, extending to the Massachusetts Institute of Technology (MIT), Stanford University, the University of Illinois at Urbana-Champaign, and the University of California at San Diego (UCSD). By the middle of the decade, advanced facilities for computer music were being developed at a number of leading institutions. Stanford, for example, established the Center for Computer Research in Music and Acoustics (CCRMA) in 1975, and this development was to prove especially important for the continuing work of Chowning.

In the same year the Institut de Recherche et Coordination Acoustique/Musique (IRCAM) purchased a dedicated mainframe computer, pending the official opening two years later of this major new research center in Paris, under the direction of Pierre Boulez. The particular importance of IRCAM in shaping the development of computer music from the late 1970s to the present day will become evident in due course, impacting both directly and indirectly on the work of many of the composers who have made significant contributions to the development of the medium over the years. At the same time, it is important to recognize that a wider perspective on the evolving genre embraces many other notable achievements in both technical and creative contexts, and these contributions are reflected in the choice of composers selected for closer study.

The progression from the exclusivity of mainframe computing to the extensive range of powerful resources for composing computer music that are now available to the individual in a personal computing environment is a fascinating subject of study, and key elements of this evolutionary process will emerge in successive chapters. The first stages in terms of technological change were already well underway by the end of the 1960s. A key driver in this context was a growing demand for computers that could be produced at a significantly lower cost, thus balancing increased accessibility by a wider community of potential users with the consequences, at least initially, of having to accept a reduced functionality. As the years progressed, advances in computer design ensured this differential in performance became increasingly reduced, assisted to no small extent by the development of specialist fast “front-end” processors that could handle the heavy processing requirements of audio and video applications. Indeed, the commanding advantages of mainframe computing
were already facing increasingly significant challenges from other quarters. Few could have predicted, for example, that the invention of the microprocessor in 1972 and subsequent developments based on its technology would in due course materially challenge and ultimately replace the technology of traditional computing architectures.

The first stages in this process of progressive miniaturization, from mainframe to minicomputer, are charted in Chapter 2, which considers the circumstances that led Barry Truax to compose \textit{Riverrun} in 1986 at Simon Fraser University (SFU), British Columbia. Truax has become well known for his pioneering work with granular synthesis, a technique investigated by Curtis Roads in the early 1970s. He first came into contact with a minicomputer at the Institute of Sonology in Utrecht in 1971, his two-year period of study at this important center for computer applications in music leading him to develop some of the very first programs to generate sounds directly from a computer in real time. Hitherto the programming environment of traditional mainframe computers required all such materials to be generated in a non-real-time mode, the sonic results being accumulated in a digital format as a data file for subsequent playback directly via a digital-to-analog converter. Truax's acquisition at SFU of a physically smaller but more powerful minicomputer and a pioneering front-end digital signal processor to speed up computation in 1981 facilitated the development of a fully interactive and real-time environment for composing works by means of granular synthesis, of which \textit{Riverrun} is a striking example.

Attention then turns to developments at IRCAM, and in particular the pioneering work of the composer Philippe Manoury. As mentioned earlier, a notable feature of IRCAM was the initial emphasis on mainframe computing applications. Although significant use was made of this technique, for almost a decade a number of researchers chose to concentrate instead on developing facilities that were specifically designed for real-time computer music synthesis and signal processing. As was to prove the case with Truax, a particular incentive was the prospect of working with such resources interactively, not merely in a composing context but also in terms of live performance. As a background to the study of Manoury's \textit{Pluton} (1988) these IRCAM-based initiatives are studied in detail since they were materially to influence the development of some of the most significant resources widely used today for both the composition and performance of computer music.

The next chapter studies the work of Hildegard Westerkamp in the context of her work with soundscape composition, a distinctive genre of computer music that concentrates on exploring the creative possibilities of naturally produced sound materials. Born in Germany, Westerkamp emigrated to Canada in 1968 and studied at the University of British Columbia, before joining the World Soundscape Project at Simon Fraser University, at the time led by Raymond Murray Schafer. Westerkamp has since become a leading composer, radio artist, and sound ecologist.\footnote{The piece of Westerkamp to be studied in detail, \textit{Beneath}}
the Forest Floor, was completed in 1992 in Toronto, toward the start of a decade that was to prove of particular significance in the evolution of computer music as the speed of both technical and musical development gathered pace.

In Chapter 5 the chronology now returns to developments in Paris, and the work of composers associated with the Groupe de Recherches Musicales (GRM), a major center of creative activity originating from the pioneering work of Pierre Schaeffer in the late 1940s and 1950s, in the first instance developing his concepts of musique concrète. This school of composing and its associated aesthetics exemplify a musical style that over the years has progressed from analog to digital technologies and been explored not only by members of GRM but also by other composers, working elsewhere, not only in Europe but also America, notably in Canada. Although for many years GRM was reliant on analog technologies, the transition to the digital domain resulted in a suite of composing resources that have proved to be unique and highly influential in the wider context. A study of the work of Francis Dhomont provides a significant insight into these important musical and technical developments, leading in turn to a detailed study of his work Phonurgie, completed in 1998.

At the start of the 1990s the true potential of the personal computer as a self-contained and increasingly powerful resource for composing computer music had yet to be fully grasped, but by the end of the decade it was becoming clear that the desktop environment would eventually replace even the powerful computer workstations that had been developed for high-end processing applications during the 1980s. It is thus all the more remarkable that a UK initiative dating from 1986 should have established a notable benchmark in this context at such an early stage. Known as the Composers Desktop Project (CDP), the associated group of pioneers set out to create composing resources that could match the capabilities of those provided by the major computer music institutions, but at the same time be affordable for individuals. This development is considered in the next chapter, which focuses on the work of Trevor Wishart in this context, both as a technical innovator and also a major composer, leading in due course to the composition of Imago in 2002, which is studied in detail.

Wishart’s pioneering work with the CDP was materially influenced by the formative experiences he gained working at IRCAM as a visiting composer, an association that was to develop further as the years advanced. Another UK composer, Jonathan Harvey, was similarly to establish close links with IRCAM, resulting in a series of works that have been major contributions to the computer music repertory. His engagement with the medium is located within a creative locus that significantly embraces the world of conventional composing with acoustic instruments, thus drawing together many different aspects of contemporary composition and musical thought. The work chosen for special study, Harvey’s Fourth String Quartet (2003), made significant demands on the real-time signal processing facilities available at IRCAM, and the ways in which these were creatively explored merit close scrutiny.
Although Harvey’s direct interaction with developments in computer music were based primarily in European contexts, an important American dimension followed his appointment as professor in composition at Stanford University in 1995, creating significant opportunities for him to engage with developments at CCRMA. This highly productive cross-fertilization of perspectives is encountered again in Chapter 8, which studies the work of Cort Lippe, both as a composer and as a software developer. Having gained early experiences with the possibilities of computer music in the United States, he relocated to Europe, following in the footsteps of Truax a decade later to study at the Institute of Sonology. However, instead of then returning to the United States, Lippe moved to the Center for the Study of Mathematics and Automation in Music (CEMAMu), Paris, in 1982. Four years later he moved to IRCAM, remaining there until 1994, when he returned to the United States to take up a post at the University at Buffalo, New York. Although his initial status at IRCAM was as a visiting composer, he soon joined the staff as a technical assistant, becoming directly involved with the development of the facilities for producing sound materials in real time, including those extensively explored by Manoury. In a similar context he also came into contact with Harvey during his early exploration of the possibilities of live signal processing at IRCAM. In a creative context Lippe’s repertory has focused in particular on the composition of works for live instrumental performers and digital electronics, leading to a series of software applications that are specially crafted for individual works. The work selected for detailed study, *Music for Tuba and Computer* (2008), provides a useful perspective on the technical and creative advances that have been made in such contexts over the years.

The final chapter studies the work of Natasha Barrett, paying particular attention to her use of advanced techniques for the spatialization of sound materials in performance spaces. Interest in the use of multiple loudspeakers dates back almost to the dawn of electronic music, and a variety of techniques have been developed over the years. These range from live diffusion techniques at the mixing desk in concert performance to the advanced mapping of sound images at the composition stage to multiple playback channels. Although significant progress was made in both contexts during the 1970s and 1980s using purely analog technologies, as computers became progressively more powerful, attention soon turned to the possibilities of developing advanced and highly sophisticated algorithms for the control of spatial imaging. Barrett took a keen interest in exploring such techniques at an early stage in her career, becoming in due course one of the leading practitioners in this regard. A particular landmark in this context has been her work with the advanced spatialization facilities developed at IRCAM, and a study of *Hidden Values*, completed in 2012, provides a revealing insight into this important aspect of computer music.

This book and the accompanying online materials are designed to offer the reader several different levels of engagement with the perspectives that emerge.
For those who wish to limit their further inquiries to the key technical and musical features of the works studied, the accompanying videos of interviews with composers, and with the developers of the software tools they used, will prove especially useful in this context. For others who wish to engage more directly with the associated methods of composing, the downloadable software includes programs that model the actual techniques used in each case. The reader can also directly explore the associated techniques for themselves, and in so doing gain not only unprecedented access to the underlying creative processes, but also explore their further potential.

The study of just nine works from the computer music repertory can only provide a selective window into the world of computer music, focused in the first instance on important works that have resulted from pioneering developments over the years. However, the methodology thus used is extensible to the works of other composers and the associated technologies they have employed, and it is hoped this initiative will encourage others so to do.
John Chowning

Stria

Contexts for Stria

Max Mathews and the beginnings of software for computer music

John Chowning’s contributions to computer music have materially influenced the development of this medium, from the 1960s to the present day. In paying particular attention to his earlier work, up to and including Stria, it is important to appreciate that this critique embraces just a segment of a long and distinguished career in this regard. In a pioneering context Chowning is especially notable for two developments, the first being his research into the possibilities of digitally controlled sound spatialization, an important technique to be considered in depth in Chapter 8, and the second a distinctive and powerful technique of sound synthesis still widely used today, known as frequency modulation (FM) synthesis. These investigations took place at a time when analog methods of generating and shaping sound materials were ubiquitous, and the potential of the computer to provide a much more powerful and versatile resource for such purposes had yet to be realized.

Computer-based techniques of digital sound synthesis were pioneered by Max Mathews at Bell Telephone Laboratories, New Jersey, working with a team of co-researchers that included John Pierce, James Tenney, and Jean-Claude Risset. During the 1950s the acoustic research division of Bell Labs became increasingly interested in exploring ways and means of increasing the density of communications that could be transmitted via the telephone network. In the
first instance this research focused on the transmission of speech quality data, but in due course investigations extended to the more demanding requirements of music.

Up to this point, audio could only be transmitted in an analog format, with limited possibilities for multiplexing different telephone calls down a single data cable. Attention soon turned to the possibility of transmitting such signals digitally, using analog-to-digital and digital-to-analog converters at either end of the line to code and decode the audio information. It occurred to Mathews that the development of computer software that could directly generate audio data in a digital format might provide an effective means of testing the performance and fidelity of such a system.

Such a proposition was far from straightforward, given the embryonic state of the computer industry at this time. The first commercial computer, the UNIVAC, appeared in 1951, and it was not until 1953 that IBM made its debut with the IBM 701, followed in 1954 by the IBM 704. All these early machines were based on valve technologies, of enormous physical proportions, and they were slow and unreliable. In 1955 Bell Labs gained access to a 704 computer located in the IBM World Headquarters, New York, and it was with this machine that Mathews synthesized his first digitally generated study in 1957, The Silver Scale, a seventeen-second sequence of triangle wave tones composed by a colleague, Newman Guttman, using a nonstandard musical temperament.

Known as Music I, this simple program signaled the start of a design revolution that was to underpin the future course of digital music technology. Although this sketch was a landmark achievement the limitations of the program as a composing tool were self-evident, in particular the lack of any functions to control both the volume and the attack and decay characteristics of the individual tones. In 1958 Bell Labs acquired its own computer, a faster and more powerful IBM 7094, based on the newer technology of transistors. This facilitated the development of Music II, a more versatile program that allowed the generation of four-part polyphony with a choice of sixteen different waveforms and a facility to control their dynamic characteristics. These enhancements, however, came at a price in terms of the complexity of the coding that was required to create these textures, as well as the extra demands made on the computer itself. Mathews realized that significant improvements had to be made to the design of the software if the computer was to achieve its true potential as a facility for synthesizing music.

The starting point for a more detailed study of the techniques employed in achieving this goal involves an understanding of the mathematics involved in the representation of audio signals in a digital format. The associated principles were first articulated by Claude Shannon and Warren Weaver in 1949 and these provided an important reference point for Mathews. The schematic shown in Figure 1.1 provides a useful overview of the procedures involved in converting
a digitized waveform into an equivalent analog signal, ready for audition via an amplifier and loudspeaker.

The crucial considerations here in terms of the resulting fidelity are the frequency of the individual samples representing the waveform and their numerical accuracy. Put in the simplest terms, the speed of sample generation, referred to as the sampling rate, determines the maximum possible audio bandwidth (50 percent of the frequency) and the numerical accuracy of the individual samples determines the quality of the resulting sounds. To give a present-day example, a conventional CD contains digital audio sampled at a rate of 44,100 samples per second, allowing a maximum audio bandwidth of 22,050 Hz, with each sample quantized to the maximum resolution possible from the binary coding of sixteen-bit sample values, which can embrace integer values from +32,767 to –32,768. This equates to a basic signal-to-noise ratio of about 98 dB.

These fidelity standards have proved generally acceptable to the audio industry and the listening public, although several techniques have been employed to improve the quality further, such as using oversampling techniques to improve the accuracy of quantization. It is important, however, to appreciate that such conditions were well beyond the reach of the early pioneers of computer music. Before the era of microchip technology, converters had to be constructed from discrete electronic components and resolutions of just ten or at the most twelve bits per sample were the order of the day, as were sampling rates that rarely exceeded 20,000 samples per second. A closer look at
the frequency setting of the smoothing filter in the above schematic, for example, indicates an audio bandwidth of 5 kHz, which in turn is associated with a sampling rate of just 10,000 samples per second, as stated by Mathews in the accompanying caption.

From a present-day perspective it is difficult to appreciate the significance of the challenging conditions faced by composers during the early days of computer music. Quite apart from these fundamental problems of music fidelity, access to computers was generally restricted to a select few individuals working in large scientific institutions, and the high cost of using these resources materially constrained the allocation of computing time. The associated data processing demands of music synthesis invariably consigned such tasks to time slots scheduled in the late hours of the night. To make matters worse, the special offline technical facilities necessary to convert the results from a digital to an analog format were often in locations remote from the main computer, requiring the physical transfer of digital sound files recorded on magnetic tape from one site to another. By the time Mathews started work on Music II, both the computer and the associated converter system were located in the same building, but this was not the case for his earlier work developing Music I, which required time-consuming journeys across New York each day.

A further constraint was the time required to compute the synthesis instructions, often proving to be many orders of magnitude greater than the duration of the resulting sounds. As a consequence, even when it became possible for individual users to submit synthesis tasks directly via a computer terminal for immediate computation rather than overnight, significant delays waiting for the calculations to complete were the rule rather than the exception. Mathews realized that if composers were thus to be isolated from the processes that generate sound, it was necessary to develop a symbolic coding environment that could be readily understood and engaged with working entirely offline. Accordingly, the concept of the “orchestra” and the “score” was developed for what became generically known as the Music N family of programs. This arrangement draws on the familiar environment of an orchestra, consisting of a series of individual instruments that are activated by performance data, provided in an accompanying score.

At the heart of this coding environment, the building blocks for constructing instruments are known as unit generators, a repertory of core algorithms that embrace both synthesis and signal processing functions. The composer selects and configures the generators for each instrument, with further assistance where required from a set of mathematical functions that may be used to modify data passing from one algorithm to another. This transfer takes place at two levels, first in terms of the flow of audio data, and second in terms of the flow of control data. This dual method of linking sound-producing functions was conceived before a similar design strategy was adopted for the voltage-controlled analog synthesizer, launched by Robert Moog in 1966.
at the start of a commercial revolution that was to embrace several other manufacturers before the end of the decade, including Buchla, ARP, and EMS London. Although the technology in the latter instance requires the physical interconnection of the individual hardware components, the architecture shared many features in common with that associated with software-based digital unit generators, notably a modular design approach where different devices, such as oscillators, filters, and envelope shapers, can be freely interconnected in the manner described above.

The functional similarities between voltage-controlled synthesizers and the facilities developed by Mathews for the Music N series of programs were noted by a number of contemporary commentators, including Mathews himself. At the same time, some important differences may be identified. For example, the former provide a fully interactive working environment, generating sound in real time, whereas the latter offered essentially the converse. Furthermore, voltage-controlled synthesizers could be purchased commercially as self-contained ready-to-use systems. By the time Mathews had completed an initial version of Music III in 1960, the foundations for the subsequent significant advances in digital technologies were firmly in place, but the exclusive nature of computer music systems at the time ensured that the latter remained relatively isolated from mainstream developments in the world of electronic music for several years.

Initially Mathews’s associates at Bell Labs were primarily engineers, working at the forefront of developments in digital communications. In addition to Guttman, the head of his research unit, John Pierce, also composed a series of pioneering computer music studies during this formative period, including *Five against Seven—Random Canon* (1961) and *Variations in Timbre and Attack* (1961). It was the involvement of composers, however, that was to provide the extra dimension necessary to ensure the software fully achieved its creative potential.

The first composer to engage directly with the work at Bell Labs was David Lewin, a junior fellow in composition and theory studying with Milton Babbitt at Harvard. During 1960–1961, following a course of instruction from Mathews on the principles of coding, Lewin prepared a series of synthesis tasks, sent by post from Harvard to Bell Labs for processing and subsequent return as audio recordings. Two short studies were produced before Lewin moved on to a teaching post at the University of California, Berkeley, to pursue different interests. He was followed by James Tenney, who joined Bell Labs in 1961. Having previously studied at the Julliard School of Music and Bennington College, Tenney transferred to the University of Illinois in 1959 to study algorithmic composition techniques with Lejaren Hiller, leading to an MA degree completed in 1961. Fortuitously, his subsequent move to Bell Labs allowed him to engage directly with the final stages of refining Music III, producing a series of six pioneering compositions, including *Analog #1: Noise Study* (1961) and
Five Stochastics Studies (1962). He also produced a detailed description of the program, published in 1963. Although the subsequent development of Music IV by Mathews, completed in 1963 with assistance from Joan Miller, is generally better known, the basic design principles for the latter version were established with Music III.

Figure 1.2 provides an illustration from Tenney’s description that provides a useful introduction to the key principles involved in the design of a Music III instrument. The example comprises a simple tone generator (described here as a timbre waveform generator) consisting of a wave table (P10) with two input controls. The input on the left-hand side controls the amplitude of the output waveform, that on the right its frequency. The envelope generator uses a special amplitude function (F2), read through once for each new sonic event. The two inputs for the envelope generator, the (maximum) amplitude and the overall duration, are triggered via an associated note/event score command. The frequency value for the timbre generator supplied via the same command is also subject to dynamic variation via the vibrato generator. The function for the latter consists of a sine wave (F1), the associated amplitude control determining the depth of the vibrato and the frequency control the associated speed. The intermediate function (known as an “add” unit) combines two inputs: the core frequency of the note thus to be generated, and the vibrato function that is to be superimposed. Ironically, this early example of a Music N instrument also illustrates the basic principles involved in FM synthesis, the technique to be studied more closely in due course in terms of their subsequent implementation for the composition of John Chowning’s Stria.

The unit generators and mathematical functions available for Music III and Music IV provided a useful repertory of modular building blocks for both synthesis and signal processing tasks. The original Music IV library (1963) provided the following functions:
One of the biggest challenges during the pioneering era of computer music was a basic requirement to write all software in a code that was unique to the computer concerned. Known as an assembler language, this consists of a processor-specific instruction set, which had to be completely rewritten should the program be subsequently transferred to another computer either by choice or as a matter of necessity following a change of model. Fortunately, in the case of Bell Labs, the IBM 7094 remained in service for almost a decade, allowing Music IV to enjoy a relatively long and useful life span as a composing facility. Princeton University took a keen interest in Music IV, and in 1963 a copy of the program was transferred to a similar IBM 7094 on the campus by a team of researchers that included Hubert Howe, Godfrey Winham, and Jim Randall. It subsequently proved possible for this team to implement a number of improvements and additions, resulting in a version known as Music IVB.

By this stage it was becoming clear that writing software in low-level code not only limited its portability, but was also very time-consuming. In many instances the solution lay in a new generation of higher-level compilers, essentially interpreting programs that convert instructions written in a common language into the machine code specifically required by the host computer. Unfortunately, these advances came at the expense of overall computing efficiency, which could only be mitigated by continuing to write any time-critical processes in assembler code. Although such hybrid approaches require

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<tr>
<td>1. OUT</td>
<td>output unit</td>
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<tr>
<td>2. OSCIL</td>
<td>standard table-lookup oscillator</td>
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<tr>
<td>3. COSCIL</td>
<td>table-lookup oscillator with no phase reset</td>
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<tr>
<td>4. VOSCIL</td>
<td>table-lookup oscillator with variable table number</td>
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<tr>
<td>5. ADD2</td>
<td>add two inputs</td>
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<tr>
<td>6. ADD3</td>
<td>add three inputs</td>
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<tr>
<td>7. ADD4</td>
<td>add four inputs</td>
</tr>
<tr>
<td>8. RANDI</td>
<td>interpolating band-limited noise generator</td>
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<tr>
<td>9. RANDH</td>
<td>sample-and-hold band-limited noise generator</td>
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<tr>
<td>10. MULT</td>
<td>multiply two inputs</td>
</tr>
<tr>
<td>11. VFMULT</td>
<td>table-lookup unit</td>
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<tr>
<td>12. RESON</td>
<td>ring-modulation resonant wave generator</td>
</tr>
<tr>
<td>13. FILTER</td>
<td>second-order all-pole band pass filter</td>
</tr>
<tr>
<td>14. LINEN</td>
<td>linear envelope generator (trapezoidal)</td>
</tr>
<tr>
<td>15. EXPEN</td>
<td>single-scan table-lookup envelope</td>
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additional work developing suitable protocols for communicating between the two machine operating levels, the subsequent benefits were often to prove significant.\textsuperscript{16} During the 1960s and early 1970s the language of choice for scientific users was FORTRAN (FORMula TRANslating), and a subsequent version of Music IVB completed in 1967 at Princeton, known as Music IVBF, used FORTRAN for the interpretation and compilation of synthesis instructions and assembler code for their execution.

During the mid-1960s Mathews became increasingly concerned with the development of a truly machine-independent version of Music IV that could be ported from one computer to another with the minimum of difficulty. The forthcoming replacement of the IBM 7094 by the much more powerful IBM 360 at Bell Labs, requiring the use of an entirely different assembler language, made this issue a matter of pressing importance. The initiative here was taken by Arthur Roberts at the Argonne Laboratories, Chicago, who developed a pilot version known as Music IVF in 1965. However, Mathews completed the definitive, all-FORTRAN version in 1966, known as Music V, subsequently installed in a number of institutions worldwide. The inevitable loss in processing efficiency, however, left others at the time less than convinced that this was necessarily the best way forward.

By the end of the decade other institutions had taken an interest in acquiring Music N software, notably the Massachusetts Institute of Technology (MIT) and Stanford University, and in both cases optimizing processing speed was considered the greater priority. As will be discussed further below, Stanford took the initiative producing Music 10, specially configured for the DEC PDP-10 mainframe computer in 1966. In a similar vein, Barry Vercoe, working at MIT, completed Music 360 for the IBM 360 in 1969. Fortunately, both of these third-generation computers remained in service worldwide until the early 1980s, and the subsequent IBM 370, introduced in the mid-1970s as a replacement for the 360, used the same assembler code.

The 1970s had also seen the introduction of the PDP-11, a minicomputer that was to prove especially important for several computer music initiatives, and some of these will be discussed in later chapters. This product of a new generation of more affordable and physically smaller computers opened up the possibilities of computer music to a number of institutions for the very first time, and Vercoe was quick to grasp the significance of this rapidly expanding market. Accordingly, he developed a version of Music 360 written in Macro-11, the PDP-11 assembler code, releasing Music 11 in 1976. Conversely, during the late 1970s, Richard Moore and Gareth Loy at the University of California, San Diego (UCSD) developed Cmusic, written for the DEC VAX, the computer that replaced the PDP-10. Like Music V this was written entirely in the higher-level programming language C, which has become one of the key resources for developing computer applications. The steady improvement in computing speeds since the late 1960s mitigated the consequential loss in processing efficiency,
and this continuing trend encouraged Vercoe to release a C-based version of Music 11 in 1986. This program, Csound, finally secured the legacy of Mathews’ pioneering work in computer music for use by future generations. Freely available via the Internet, this facility embraces an extensive repertory of synthesis and signal processing tools, available to all and still actively maintained by an extensive worldwide user community.

A material issue associated with the pioneering years of computer music relates to the continuum that extends from quasi-instrumental styles of composition, based on traditional methods of working with “note/events,” to more abstract concepts of timbre, embracing the multitude of ways in which the associated spectral components can be creatively manipulated. In terms of balancing familiarity with the unknown, the significant time delays experienced between submitting a Music N task for computation and auditioning the outcome provided a powerful inducement for composers to embrace more imitative approaches rather than engage proactively with the unfamiliar. It was the particularly imaginative approach taken by Jean-Claude Risset, appointed as composer in residence at Bell Labs in 1964, that was to prove of material significance in overcoming more conservative attitudes in this regard.

**Jean-Claude Risset and timbral synthesis**

Risset was trained as a physicist and mathematician at the École Normale Supérieure, Paris, studying also piano with Robert Trimaille and composition with André Jolivet. This combination of studies provided strong foundations for his subsequent engagement with the creative possibilities of computer music. As a student in the 1950s it is reasonable to assume that he would have engaged with Pierre Schaeffer’s pioneering work with musique concrète, but this was not the case. Risset offers the following explanation:

I wanted to increase the functional part of timbre in my composing. Yet I resisted turning to electronic music—in Paris, it was mostly Pierre Schaeffer’s musique concrète. I felt that electronic music yielded dull sounds that could only be made lively through manipulations which, to a large extent, ruined the control the composer could have over them. On the other hand, musique concrète did open an infinite world of sounds for music—but the control and manipulation one could exert upon them was rudimentary with respect to the richness of the sounds, which favored an esthetics of collage. Both techniques seemed to me to rely on ready-made objects or processes, which the composer could only warp for his purposes.

These observations are revealing. Of particular interest is his initial rejection of techniques that were central to the aesthetics of Pierre Schaeffer and his associates. His views, however, were materially to change when he discovered that the digital computer could provide the degree of control and manipulation
he was seeking, not only in terms of synthesis from first principles, but also in the processing of acoustically generated sounds.

Prior to the early 1960s, knowledge of the work being carried out by Mathews at Bell Labs had not extended significantly beyond those directly associated with the institution. This situation was to change in 1963 with the publication of a landmark article by Mathews on his work in the journal *Science*, with an international readership that extended to a much wider research community, including Risset. This article was to prove a major stimulus for Risset in terms of seeking ways and means of directly engaging with the possibilities of computer music, and having secured sponsorship from a French research funding agency he arrived at Bell Labs the following year. His preoccupation with timbre led him to analyze the complex characteristics of acoustically generated instrumental sounds in terms of the individual spectral components, using the data to resynthesize the sounds using Music IV. His work modeling brass tones, notably trumpet sounds, was especially significant in this context, and, as will be seen in due course, his discoveries were to prove of special interest to Chowning.

Compulsory national service required Risset to return to France, 1965–1967, and by the time he returned to Bell Labs work on Music V was already well advanced. Nonetheless he was able to contribute a number of useful refinements to the software while at the same time starting to explore its creative potential as a composing resource. His first work, *Little Boy* (1968), was based on a play by Pierre Halet recalling the dropping of the first atomic bomb on Hiroshima in 1945, seen through the mind of the pilot. The transformations of timbre that are used to underpin the musical argument here established an important repertory of synthesis and signal processing techniques for his subsequent compositions, including procedures such as the manipulation of harmonic arpeggios and spectral processing of selected parameters within individual sounds while retaining the key characteristics of others. His work in the latter context anticipated the repertory of techniques based on the principles of linear predictive coding and phase vocoding that were to be extensively explored by computer music composers in subsequent decades.

The most significant piece to emerge from Risset’s work at Bell Labs was *Mutations*, completed in 1969 just before his final return to France. This was a commission from Groupe de Recherches Musicales (GRM) in Paris, and in many respects it represents an extension of ideas initially pursued in *Little Boy*. The following comments by the composer provide a helpful perspective on his emerging thinking at this time:

[The works] implement the scientific developments that made it possible to imitate acoustic instruments—such as brass, clarinet, piano and percussion—and to compose the internal structure of sound, in particular by:
John Chowning: Stria

- synthesizing gong-like or bell-like tones composed as chords with a prescribed harmony, hence prolonging harmonic control within the realm of timbre
- dispersing in time harmonic components that usually sound together, just as a prism disperses white light
- intimately transforming “inharmonic” sounds, that is, sounds made up of non-harmonically related components. By changing the amplitude envelopes of the components, I could leave the underlying harmony unchanged but influence the listener toward either focalized, synthetic perception (hearing separate sound objects or events) or distributed, analytic perception (hearing textures)
- implementing pitch paradoxes. For the compositions mentioned above, I manufactured tones with fractal structures (in other words, tones that look similar when examined at different scales) that seem to glide indefinitely up or down in pitch, or seem to go down in pitch but end up much higher than where they started.

Mutations, for example is a metaphoric journey from discontinuous pitch scales into a continuum of pitch. This transition happens through going to higher harmonics separated by narrowing intervals.  

These works were arguably the most advanced and insightful computer-generated works to emerge from the 1960s, very much establishing the shape of things to come, not least in the context of exploring the creative potential of the complementary techniques of analysis and resynthesis, where a study of the spectral characteristics of naturally generated sounds can provide not only a detailed understanding of their spectral content, but also the data necessary to create entirely new variations and transformations.

Whereas Risset’s work at Bell Labs was predicated in the first instance on the study of acoustic instrument sounds, the transformations he achieved in terms of composing works such as the above were undoubtedly ground-breaking. Perhaps the most significant legacy of his work at Bell Labs was an Introductory Catalog of Computer-Synthesized Sounds, completed in 1969, complete with the Music V orchestras and scores required to reproduce them. One further characteristic of Mutations is of particular significance at this point. In terms of the repertory of synthesis techniques employed, it was the very first substantive work to make use of John Chowning’s pioneering algorithms for FM synthesis, and it is to these important developments that our attention is now turned.

John Chowning and the evolution of FM synthesis

John Chowning’s career started with a period of military service during the early 1950s, including studies at the US Navy School of Music. In 1956 he enrolled at Wittenberg University, Springfield, Ohio, completing a music degree in 1959. A scholarship then took him to Paris to study with Nadia
Boulanger, thus bringing him into direct contact with the forefront of developments in contemporary music in Europe, including the emerging genre of electronic music.

On his return to the United States in 1962, Chowning commenced postgraduate studies with Leland Smith at Stanford University, completing his doctorate in 1966. Like Risset he first became aware of developments at Bell Labs via the earlier-mentioned article on computer music by Mathews published in *Science* in 1963, resulting in a visit to Mathews at Bell Labs in the summer of 1964. He returned with a copy of Music IV coded as a deck of punched cards. After some internal negotiations he was able to install the program on an IBM 7090 in the computer science department at Stanford, using a shared data disk facility to transfer the output files directly to a small PDP-1 computer located in the artificial intelligence department. The latter included an X-Y plotter display that could be configured to convert digital audio into an analog format for reproduction via a conventional loudspeaker.

This arrangement was not entirely satisfactory. In particular, the data conversion facilities only provided a monophonic output of limited fidelity. Work soon commenced on a matrix of four digital-to-analog converters specifically designed by Joe Zingheim for audio applications. This facility, completed in 1966, created for the first time a multichannel composing environment for computer music. Each of the four output channels offered twelve-bit sample resolution at a maximum speed of 25,000 samples per second. In a related context the installation of a DEC PDP-6 computer provided a powerful incentive for the development of a new version of Music IV, written specifically for this computer by John Chowning and James Moorer. The PDP-6 was soon replaced by a PDP-10, which became a popular mid-range computer for a number of research institutions worldwide. Fortunately, it also used essentially the same instruction set as the PDP-6, and with assistance from David Poole, Music 10 was completed in 1966. The award of Chowning’s doctorate in the same year led to a position as a member of the faculty, along with the start of an intensive period of personal research into the development of synthesis algorithms for computer music.

Although he was aware of Risset’s work during the early 1960s investigating the modeling of instrumental sounds by means of additive synthesis techniques, Chowning did not directly pursue these possibilities at this time, further progress on Risset’s part, as noted earlier, being suspended while he returned to France for national service. Instead Chowning started to explore other ways of generating music, including the technique outlined in James Tenney’s earlier article on Music III discussed above, that of applying vibrato to pitched sounds.25 Although initially unaware of the true significance of this methodology, a sequence of events led him to discover the possibilities thus created for synthesis by means of frequency modulation.
His most important first step in this context came about as a result of a simple data coding error. It was a chance mis-keying of a vibrato speed of one hundred cycles per second instead of ten cycles that led him to discover that at higher speeds of pitch, modulation frequency sidebands are generated either side of the primary pitch. The functional characteristics of frequency modulation in mathematical terms were already well known to the telecommunications industry in the context of broadcasting television and radio signals, but their significance when applied directly to frequencies within the audio spectrum was almost unknown.

Whereas analog frequency modulation techniques were already being explored by composers using commercial voltage-controlled synthesizers (and there are some notable earlier precedents in this context that can be identified in the works of leading pioneers of electronic music, such as Karlheinz Stockhausen), such composing environments did not permit the refinement of parameter control possible in the digital domain. Crucially, the mathematics of frequency modulation facilitate the generation of a rich and varied repertory of dynamically varying timbres, the sophistication of which is determined by the scope and nature of the functions used to regulate the modulating characteristics. Such a measure of control was only possible in a fully programmable digital environment.

In 1973 Chowning published what has become universally acknowledged as the standard reference text on the implementation of frequency modulation in the audio spectrum, and the following summary of the key features discussed in the article provides useful foundations for the subsequent study of Stria. The diagram in Figure 1.3 illustrates the organization of a pair of oscillators to create a basic FM generator (the “P” values refer to the fields containing the data values on the score card used to activate the associated instrument at the designated point in time).

The significant components here are the carrier frequency, known in FM theory as the “c” component; the modulating frequency, known as the “m” component; and the deviation component, known as the “d” component. If the modulating frequency is very low, say eight to ten cycles per second (hertz) then the effect will be perceived as a pitch vibrato, the depth of which being determined by its amplitude. If, however, the modulating frequency is increased beyond about 20 Hz, the ear can no longer perceive the pitch variations as a function of time. Instead, a series of discrete side band frequencies are generated either side of the carrier frequency, at frequency intervals and individual amplitudes controlled by the values of the “m” and “d” parameters. As already noted, the deviation value is the amplitude input to the controlling oscillator, but since this parameter determines how far the modulated frequency will fluctuate either side of the central, or carrier frequency, its numeric value directly translates into a frequency parameter. Thus, if the carrier frequency is,