The Digital Computer as a Musical Instrument

A computer can be programmed to play "instrumental" music, to aid the composer, or to compose unaided.

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With the aid of suitable output equipment, the numbers which a modern digital computer generates can be directly converted to sound waves. The process is completely general, and any perceivable sound can be so produced. This potentiality of the computer has been of considerable use at the Bell Telephone Laboratories in generating stimuli for experiments in the field of hearing, and for generating speech sounds and connected speech in investigations of the factors which contribute to the intelligibility and naturalness of speech.

The quality of sound is of great importance in two fields—that of speech and communication and that of music. Our studies at the Bell Laboratories in the first of these fields have led us, over the past few years, to related studies in the production of musical sounds and their organization into musical compositions. I believe that this by-product of our work on speech and hearing may be of considerable value in the world of music, and that further work in this direction will be of substantial value in furthering our understanding of psychoacoustics.

There are no theoretical limitations to the performance of the computer as a source of musical sounds, in contrast to the performance of ordinary instruments. At present, the range of computer music is limited principally by cost and by our knowledge of psychoacoustics. These limits are rapidly receding.

In addition to generating sound, the computer can also function as a machine for composing music. It can either compose pieces based entirely on random numbers generated by itself or it can cooperate with a human composer. It can play its own compositions.

Here I first describe the process for converting numbers to sounds, then I describe a program for playing music. Next I consider a psychoacoustic problem which is typical of those posed in attempts to make more interesting sounds. Finally, I look to the future, to the time when the computer is itself the composer.

Sound from Numbers

How can the numbers with which a computer deals be converted into sounds the ear can hear? The most general conversion is based upon the use of the numbers as samples of the sound pressure wave. A schematic diagram of this process is shown in Fig. 1. Here a sequence of numbers from the computer is put into an analog-to-digital converter, which generates a sequence of electric pulses whose amplitudes are proportional to the numbers. These pulses are smoothed with a filter and then converted to a sound wave by means of an ordinary loudspeaker. Intuitively, we feel that if a high enough pulse rate is used and the amplitudes of the pulses are generated with sufficient precision, then any sound wave can be closely approximated by this process. Mathematically, it has been established (*1*) that this conclusion is correct. A sound wave with frequencies from 0 to B cycles per second can be generated from a sequence of two B pulses per second. Thus, for example, by running our computer at a rate of 30,000 numbers per second, we can generate sound waves with frequencies from 0 to 15,000 cycles per second. Waves in this frequency range are about the only ones the human ear can perceive.

The signal-to-quantizing-noise ratio of the sound wave depends on the accuracy with which the amplitudes of the pulses are represented. Computers deal with a finite number of digits and, hence, have limited accuracy. However, the computer limits are more than sufficient acoustically. For example, amplitudes represented by four-digit decimal numbers, are accurate to within 1 part in 10,000, an accuracy which represents a signal-to-noise ratio of 80 decibels; this is less noise than the ear can hear, and less noise than would be introduced by any audio equipment, such as the best tape recorder.

The sampling process just described is theoretically unrestricted, but the generation of sound signals requires very high sampling rates. The question should immediately be asked, "Are computers of the type now available capable of generating numbers at these rates?" The answer is "Yes," with some qualifications. A high-speed machine such as the I.B.M. 7090, using the programs described later in this article, can compute only about 5000 numbers per second when generating a reasonably complex sound. However, the numbers can be temporarily stored on one of the computer's digital magnetic tapes, and this tape can subsequently be replayed at rates up to 30,000 numbers per second (each number being a 12-bit binary number). Thus, the computer is capable of generating wideband musical sounds. Because of the cost of computer time, we often limit our studies to those for which the computer is run at lower rates, such as 10,000 numbers per second—a rate which yields a bandwidth of 5000 cycles per second.

The direct conversion of numbers to sound is only one of the ways in which the computer can generate sounds. An alternate procedure is to use the numbers from the computer to control electronic apparatus such as oscillators and filters, which, in turn, generate the sounds. These processes have been carried out by the Radio Corporation of America music synthesizer (*2*) and by a machine constructed at the University of Illinois (*3*). This procedure has the advantage that a much lower rate

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find these data in the literature, J. C. Tenney made a small study. The results are shown in Fig. 4. Here the just-detectable difference in the rise times of two tones is shown as a function of the shorter of the two rise times. These data indicate that, for rise times longer than about 5 milliseconds, a ratio of 3 to 2 is just detectable. For times shorter than 5 milliseconds, a difference of 1.5 milliseconds is necessary. Using these data, the composer can select a "scale" of attack functions which are separated by intervals that are equal in terms of the listener's ability to differentiate between the attack functions. Such data are typical of those required by a composer.

Composing with the Computer

So far I have described use of the computer solely as a musical instrument. The composer writes one line of parameters for each note he wishes played and hence has complete control of the note. He is omnipotent, except for lack of control over the noise produced by the random-number unit generators. Here a minor liberty is allowed the computer.

However, composing-programs are a reasonable area of computation, and work in this direction has already been done by Hiller (*5*), Olson (*6*), Brooks (*7*), and others. A number of different approaches can be taken toward composition by computer. At one extreme, the computer can be given a set of rules, plus a random-number generator, and can simply be turned on to generate any amount of music. Hiller's work is perhaps closest to this extreme. In the opposite direction, the human composer can maintain close control of the music, using the computer merely to avoid some of the repetitious and tedious work involved in representing his musical ideas. Once a theme with many notes has been written, a program can be devised for repeating the theme by means of a single instruction. Furthermore, the theme can be modified in simple ways: it can be transposed to another pitch range or played upon a different instrument; its tempo can be changed or its loudness modified. Harmonization of the theme according to simple rules is possible. Other means of modifying or developing a theme in interesting ways may be forthcoming. The composer could, perhaps, form a composition from a set of thematic material, which he supplied, and a set of fixed transformations.

At present, the music-playing program has been modified so as to make transformational development of a theme possible. Certain of the simplest transformations have been programmed. These include all those mentioned above, with the exception of harmonization. As yet not enough music has been generated to assess the significance of this approach.

A slightly different method has been tried by Tenney. His approach is a compromise between a purely random and a completely specified composition. The parameters of the individual notes of the composition are generated as a sequence of independent random numbers by a random-number routine. However, the average value and the variance of these parameters are specified by the composer as functions which change slowly throughout the composition. The "score" of a section of one of Tenney's works is shown in graphic form in Fig. 5. The means and variances of the note-durations, loudness, and other parameters of the various voices are controlled. Indeed, the number of voices playing at a given time is controlled. By this relatively simple algorithm, a long-range structure which can be clearly recognized by the ear is imposed on the composition. Thus, one of the characteristic shortcomings of random compositions —a lack of long-range structure—can be overcome.

The use of computers as an aid in composition is still very new. We hope that by this means the composer can avoid having to write out all the individual notes in a piece of music in order to express his ideas—that he will be able, rather, to write directly in parameters that are much more closely related to his musical objectives, letting the machine generate the individual notes. Whether this objective can be attained remains to be seen.

The Future of Computer Music

I have indicated how almost any sound can be produced by treating the numbers generated by a computer as samples of the sound pressure wave. A very high sampling rate is required, and, if this process is to be useful musically, programs for generating samples from the parameters of notes must be written. A broad set of these programs is now available and has been used for playing, on an experimental basis, a wide range of music. Additionally, studies are being made on possible uses of the computer as an aid in composing. In such studies the computer usually plays its own compositions and constitutes a composer-player team.

Computer music appears to be very promising technically. However, the method will become significant only if it is used by serious composers. At present, our goal is to interest and educate such musicians in its use. We believe that competent work in the field can benefit not only music but the whole field of psychoacoustics.

References and Notes

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3. A musical output for the csx-1 computer in the Coordinated Science Laboratory at the University of Illinois was constructed by J. Divilbis. No written description is as yet available.
4. "Music from Mathematics." Decca record DL 9103 Monaurl or DL 79103 Binaurl.
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