deviation of our values from those of the NBS (1955) scale is, in general, within the limits of accuracy (from $\pm0.01°$ to $\pm0.02°K$) stated for that scale. The lowest point, at 11°K (a difference of $-0.01°K$), may indicate an actual deviation between the two scales.

The acoustical thermometer has made a worthwhile contribution to absolute thermometry in regions below 20°K. It has resulted in the establishment of a provisional scale [NBS Provisional Scale 2-20 (1965)], which covers a hitherto uncharted range of temperature (5° to 10°K); calibrations against NBS Provisional Scale 2-20 (1965) have been performed for nearly a year. It is expected that the instrument will find more extensive absolute-thermometry uses and will be valuable in the investigation of other problems in the field of low-temperature research.

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Research in Music with Electronics

Effects of modern scientific ideas and technology on the analysis and composition of music are surveyed.

Lejaren Hiller and James Beauchamp

The juxtaposition of the words *research* and *music* may seem curious to many scientists. On the other hand, as one of us (L.H.) has remarked (*1*, p. 11), "music has been a subject of considerable fascination to philosophers and mathematicians, even often being classified as a form of mathematics and thus considered to reveal natural law in terms of mathematical logic. . . . [If] this attitude strikes many of us as a bit peculiar today, perhaps it is . . . largely a consequence of the rather extreme views developed during the period of the nineteenth century Romantic tradition." In effect, we can say that music is more than a form of entertainment, that it can be subjected to rational investigation, the results of which contribute significantly to our knowledge of human communication.

This coupling of the concepts of music and research seems to be on the increase today; this has come about particularly since the end of World War II, when electronic techniques began to have their first really strong impact on music considered as a creative activity. At present this growing congruity of concepts is not only changing the thinking of creative people in the field of music but also attracting professional people from other fields—notably technical ones like electrical engineering and mathematics.

Research in music today extends well beyond historical documentation. the traditional subject of musicological research. It includes new work in acoustics and music theory and incorporates applications of new theo-

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retical developments in science, such as information theory and modern psychological theory. To illustrate this point, we shall review here some of the work we are carrying out in the Experimental Music Studio at the University of Illinois. What we are doing there is by no means unique; on the other hand, our work deals with many important aspects of music research now going on in both this country and Europe.

First, however, we shall review briefly some historical background. Curiously, no really authoritative history of the development of acoustics is available today. Some years ago D. C. Miller (*2*) published a brief account of the history of the science of sound, but this has been out of print for a long time.

In ancient times music was considered to reveal natural law. The Pythagorean approach was concerned with finding explanations of music in terms of small whole numbers; perhaps the most useful result of that approach was the discovery of the way the lengths of strings can be subdivided to produce the harmonic series. One of the useful and interesting authors of that time was Aristoxenus (*3*), who clearly understood the concept of ordering and of discarding random structures when composing music and who also discussed musical perception in terms that seem not entirely irrelevent even today.

The Renaissance is thought to have been the period when the rational, empirical study of music theory and acoustics really began. One of the important treatises of this time is Père Mersenne's *Harmonie Universelle*, of 1636 (*4*). Mersenne is credited with having been the first to recognize clearly the relationship of musical timbre to partials distribution. The development of classical acoustics from this point on may be said, we think, to culminate in the work of Helmholtz, as summarized in his treatise *On the Sensations of Tone* (*5*). Helmholtz not only laid the basis for modern theories of hearing but also extensively investigated the nature of musical timbre; the nature of scales, tunings, and consonance and disconsonance; and the properties of musical instruments. Since his work coincides with the high point of the western-European classic-romantic tradition in music, his esthetic attitudes conform to that tradition.

Helmholtz's work, as important as it still is, was limited by factors not entirely under his control. In particular, he had no electronic instrumentation; therefore, many of his results were of necessity qualitative or provisional. Fortunately, the 20th century has provided in growing measure the equipment necessary for carrying out the precise experimentation needed to extend modern musical acoustics research beyond the point reached by Helmholtz.

Electronics has not just affected acoustical research as such. It is also altering almost all fields of music, from composition and performance to the distribution of music to the general public. Not all of this has been put to the best possible use, as, for example, anyone listening to American radio today can attest. On the other hand, the development of electronic music has revived composers' concern with acoustics, while the development of modern recording processes has widely expanded the opportunity to hear and evaluate music of every period and from every part of the world.

Electronic music, as such, has developed thus far in four main steps (*6*). The first step, which dates from about 1920, was the design of electronic instruments intended for performance in the usual sense. Although the electronic organ is the most impressive technical achievement in this field, the older and simpler monophonic electronic instruments, like the theremin, the trautonium, and the *ondes Martenot*, have interested composers more. The reason for this is simple. These instruments provide the composer with new timbres, whereas the electronic organ is designed to simulate the already known timbres of the pipe organ.

The second step was the development of electronic tape music. This came about as a consequence of the invention of the tape recorder during World War II. With this instrument, composers for the first time had a practical means of directly composing a finished composition without recourse to performance. New electronic tape music compositions are now being prepared in many places in the United States and Europe. Major centers for the composition of electronic music are studios at the University of Illinois and Columbia University in this country, at the University of Toronto in Canada, and, in Europe, at broadcasting stations in Paris, Cologne, Milan, and Warsaw; at the University of Utrecht in Holland, the Technische Universität in Berlin, and at other European universities; and at the plants of industrial firms, such as Siemens und Halske in Munich.

The third step was the development of electronic-music synthesizers. Although the concept of a music synthesizer goes back at least to 1906, when Thaddeus Cahill developed his "Telharmonium" (*7*), the first really practical synthesizer was built by Harry Olson at the Radio Corporation of America in 1955 (*8*). Synthesizers differ from conventional electronic-music equipment in that they accept coded instructions for the production of a complex combination of many sounds and produce that combination more or less in one direct operation. The second electronic-music synthesizer built by RCA is now located at Columbia University as a main installation of the Princeton-Columbia Electronic Music Project. It has been used principally by Milton Babbitt, for compositional projects and psychoacoustic research investigations.

Finally, the fourth step was the demonstration of the possibility of employing digital computers for musical uses. The first experimental result of this sort was the composition, by means of a computer, of the *Illiac Suite for String Quartet*, in 1957. This work, which was carried out by one of us (L.H.) in collaboration with Leonard M. Isaacson, has been fully described elsewhere (*1*, chaps. 5, 6). It was, in essence, a demonstration that a computer could be programmed to generate musical scores according to either conventional musical procedures (counterpoint, ordinary rhythms, and so on) or novel procedures, such as the employment of stochastic chain processes that yield musical patterns governed by probability distributions. A short sample of music taken from the third movement of the *Illiac Suite* is shown in Fig. 1.

At the University of Illinois we have become interested in all these areas of work for both creative composition and music research. In 1959, as a consequence of the initial experiments in the use of computers for music composition, our School of Music established an Experimental Music Studio for electronic-music composition, musical-acoustics research, and studies in musical applications of computers.

Fig. 1. A section of the third movement of the *Illiac Suite for String Quartet*, showing a simple sample of computer music. [Copyright 1957, Theodore Presser Company, Bryn Mawr, Pa.; reproduced by permission of the publisher]

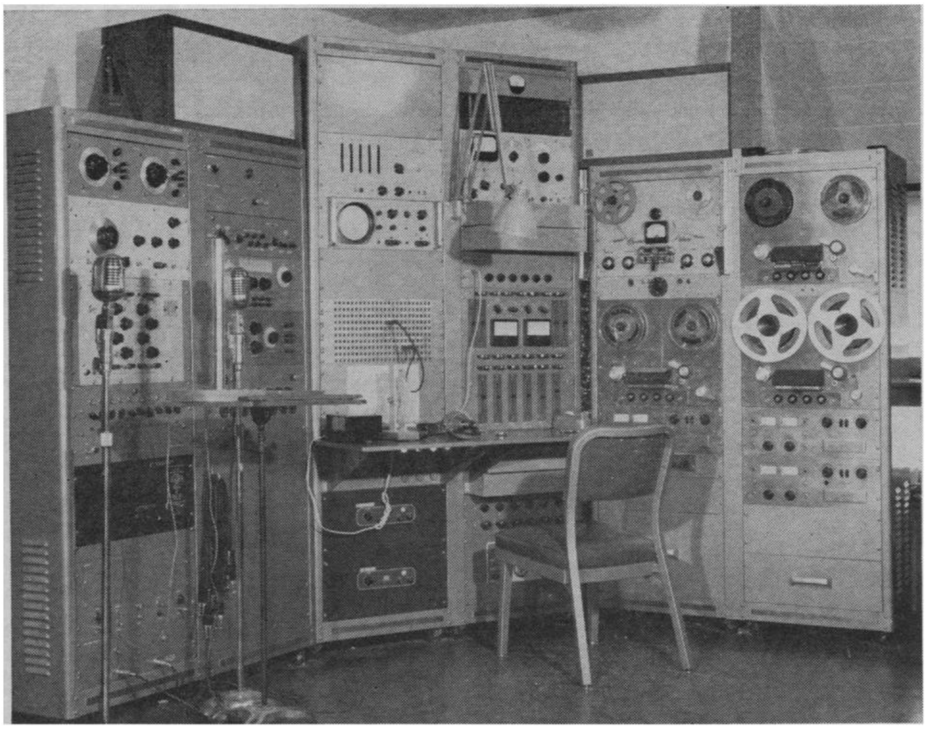

Fig. 2. Electronic-music apparatus in the Experimental Music Studio of the University of Illinois.

The principal installation in our electronic-music studio at the moment is an electronic-music console (Fig. 2) that is used primarily for the production of electronic tape music but is also used for a considerable part of our analytical work. Two successive stages in the development of this apparatus have been described elsewhere (*9*). In addition, for the past 3 years we have been developing new methods of timbre synthesis by means of voltage-controlled components incorporated in a new "harmonic tone generator," shown in Fig. 3 (*10*). As described elsewhere (*11*), this instrument permits the additive synthesis of timbres consisting of up to six harmonics in such a way that relative intensity of each harmonic can be independently set. Moreover, the various harmonics can be given independent exponential attack and decay curves and, by means of amplitude modulation, independent tremolos. The fundamental frequency of any tone generated by this device is derived from a voltage-controlled oscillator. Therefore, musical effects such as vibrato, trill, and portamento can be easily generated with this machine by means of frequency modulation. The intensities of the harmonics are unaffected by changes in the fundamental frequency, which ranges from 0 to 2000 cycles per second.

Let us now examine some of our present research concerns. We shall group these under three headings: instrumentation; analysis and synthesis of single sounds; studies of complex musical structures. The discussion concerns not only work under way but also some speculation on what the next steps should be.

Instrumentation

Studio equipment. For convenience, we shall call an electronic-music console, such as that shown in Fig. 2, and a signal generator, such as the harmonic tone generator shown in Fig. 3, "analog equipment." Instruments such as these provide means for generating, modifying, routing, controlling, analyzing, and recording and editing all types of natural and synthetic sounds. Consequently, they serve two main uses. One use is analytical, since all such equipment can be employed to generate original timbres according to specified formulas, or to control or alter existing sounds and then measure the characteristics of the resulting sounds. The second use is synthetic—that is, the equipment is used to prepare electronic tape music compositions. At the moment we are completing our inventory of sound-modifying equipment, such as modulators, formant filters, and transient generators. Among projects of this kind the following are perhaps the most essential. (i) Extension of the range of the existing harmonic tone generator from its present six harmonics to 12; (ii) construction of analog multipliers and devices for generating both exponential and nonexponential attack and decay curves for transient changes in timbre; (iii) construction of time-delay circuits and other circuits for the control of durations, attack intervals, and other time relationships; (iv) the acquisition of additional voltage-controlled signal generators, amplifiers, and filters (*12*); (v) development of a device for frequency transposition and for time compression and expansion; (vi) development of a practical device for generating sounds with inharmonic partials—that is, sounds in which the frequencies of the partials do *not* bear simple numerical relationships to one another; (vii) the analysis, with analog equipment, of harmonic tones such as those produced with ordinary musical instruments.

Digital equipment and programming. We realize that many types of signals are poorly handled by analog equipment and that errors of precision can become overriding factors that limit its use. For example, tape recording is by no means perfect even with the best equipment. In general, digital computer systems supplement analog equipment very well in the particular areas where analog equipment is least good—for example, in the analysis of complex transients and in the control of the time dimension in signal synthesis. Consequently, we now believe that a combination of the two techniques best serves the modern acoustics laboratory. We have initiated several programs of digital computer processing of musical signals and symbols; three of these are as follows.

1) Direct sound synthesis. Digital computers can be used efficiently for both analysis and synthesis of audio signals. This was first demonstrated at Bell Telephone Laboratories by Pierce, Mathews, Guttman, and Tenney (*13*). They developed a process involving the programming of a pseudo-orchestra of basic sounds (sine wave, square wave, white noise, and so on) and sound modifications (attack and decay transients, filtering, modulating, and so on) in an IBM 7094 computer and the generating, at less than real time, of the digital representation of the composite signal onto digital mag-

netic tape at a rate corresponding to a sampling rate of 10,000 samples per second. This process yields an audio high-frequency cutoff of around 5000 cycles per second. The content of the digital tape is then read back in real time through a buffer memory and a digital-to-analog converter and recorded on standard audio tape.

More recently, at the University of Illinois, there have been several developments which should lead rather rapidly to significant improvements over this generating process. First, Divilbiss (*14*) developed a very simple real-time signal-generating process for the CSX-1 computer. We now use this for producing limited variety of sounds and for generating gating signals for time and rhythm studies. Second, an analog-to-digital converter has been installed on ILLIAC II, which has been programmed for Fourier analysis of audio signals run through the system. This equipment is being currently tested with various types of complex speech and musical sounds (*15*). Third, we are currently installing a digital-to-analog system which will be operational by mid-1965. Because we are using high-speed converters, and since ILLIAC II computes more rapidly than an IBM 7094, our system is able to run on line in real time at a sampling rate of 40,000 13-bit samples per second whenever the calculations for wave forms to be converted are sufficiently rapid. We believe that real-time operation, wherever possible, is highly desirable in acoustics research. Sound-synthesis programs should be alterable during the generation of sounds so that sounds can be "shaped" by ear while the computer is in actual use.

2) Digital control of analog components. One serious objection to complete digital synthesis of audio signals is that an inordinate amount of expensive machine time is required simply to carry out trivial calculations, such as computing all the successive points on a sine wave at whatever sampling rate is being employed. We hope to install, in the near future, connections between a computer and a substantial number of our other signal generators and modifiers in order to reduce this computing load. We feel that, ideally, a computer should process only significant acoustic information that is embodied in the larger "shapes" of sound —that is, data such as formants, transient envelopes, and inharmonic content; in effect, a computer should be the controlling element of a highly sophisticated vocoder. Instrumentation for obtaining this kind of control includes connections (i) via voltage-controlled oscillators, amplifiers, and filters of the type described above, (ii) via relay circuitry, and (iii) via servomechanism drive units.

3) Music notation printout. Not only is it desirable to have direct printout in musical notation of musical information stored in a computer but it is also desirable to develop the automatic processing of musical notation as such, because music printing is, to this day, an almost completely unmechanized process that is grossly inefficient and costly. As a pioneering project, we recently developed a paper-tape-controlled music typewriter and programmed it to operate in conjunction with ILLIAC I to design and process a musical format. This work is described in a recent article (*16*). This typewriter is by no means the final solution to the problem, since it is now obsolescent mechanically and electronically. We hope eventually to replace it with a more modern printing mechanism, and to rewrite our programs for music printing for ILLIAC II because of the higher speed and capacity of this newer computer. The most promising new method for printing seems at the moment to be printing by means of programmed optical devices. With such equipment all that is required in the way of special hardware is a supply of matrix disks providing musical symbols. Very possibly we would attach this hardware to ILLIAC III rather than ILLIAC II, because ILLIAC III is a special-purpose computer designed for pattern-recognition work (*17*). The printout of materials in ILLIAC II would still be possible, however, because the two computers are functionally jointed.

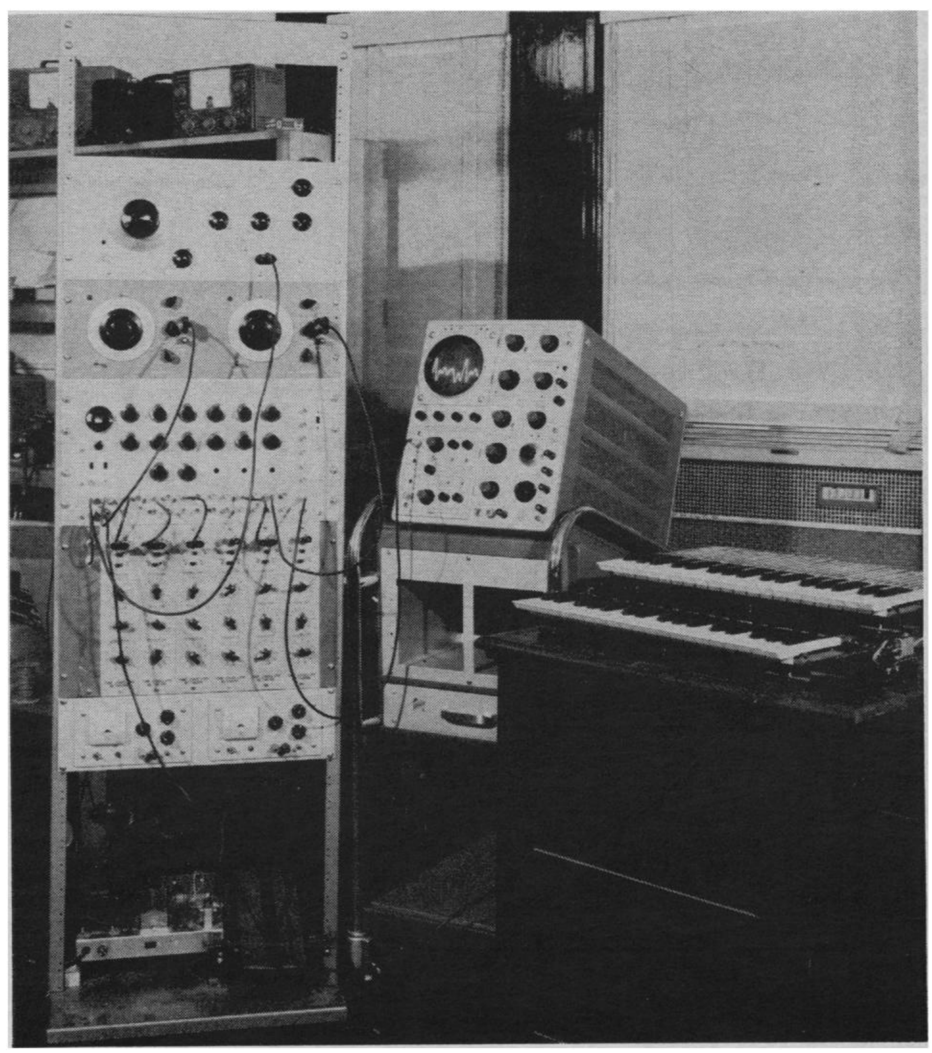

Fig. 3. The "harmonic tone generator," an instrument for additive synthesis of harmonic musical timbres.

Analysis and Synthesis of Single Sounds

Music, like speech, presents special problems for analysis. In many ways the signals are simpler to analyze; for instance, pitch is often a relatively constant factor. On the other hand, the listener to music is more acutely sensitive to parametric variations, and resynthesis is not merely a question of producing an intelligible signal. Consequently, we are currently developing a twofold approach to the study of single sounds that would involve not only the analysis of sounds produced by ordinary musical instruments but also the synthesis, by electronic means, of mathematically defined sound structures. Our projects at present include the following.

Analysis of ordinary musical sounds. These sounds are not nearly so well understood as is commonly believed. Even the formant structures characterizing the steady state have been only sketchily and incompletely measured (*18*). Published data on transients and other complex characteristics of sounds are almost nonexistent (*19*).

We are beginning to use both analog and digital techniques to evaluate those parameters that determine the high degrees of differentiation in timbre among musical sounds, taking into particular account factors such as (i) attack and decay transients of individual frequency components, including inharmonic ones; (ii) variations in frequency; and (iii) random or quasi-periodic modulations. It is important, always, to define appropriate levels of precision.

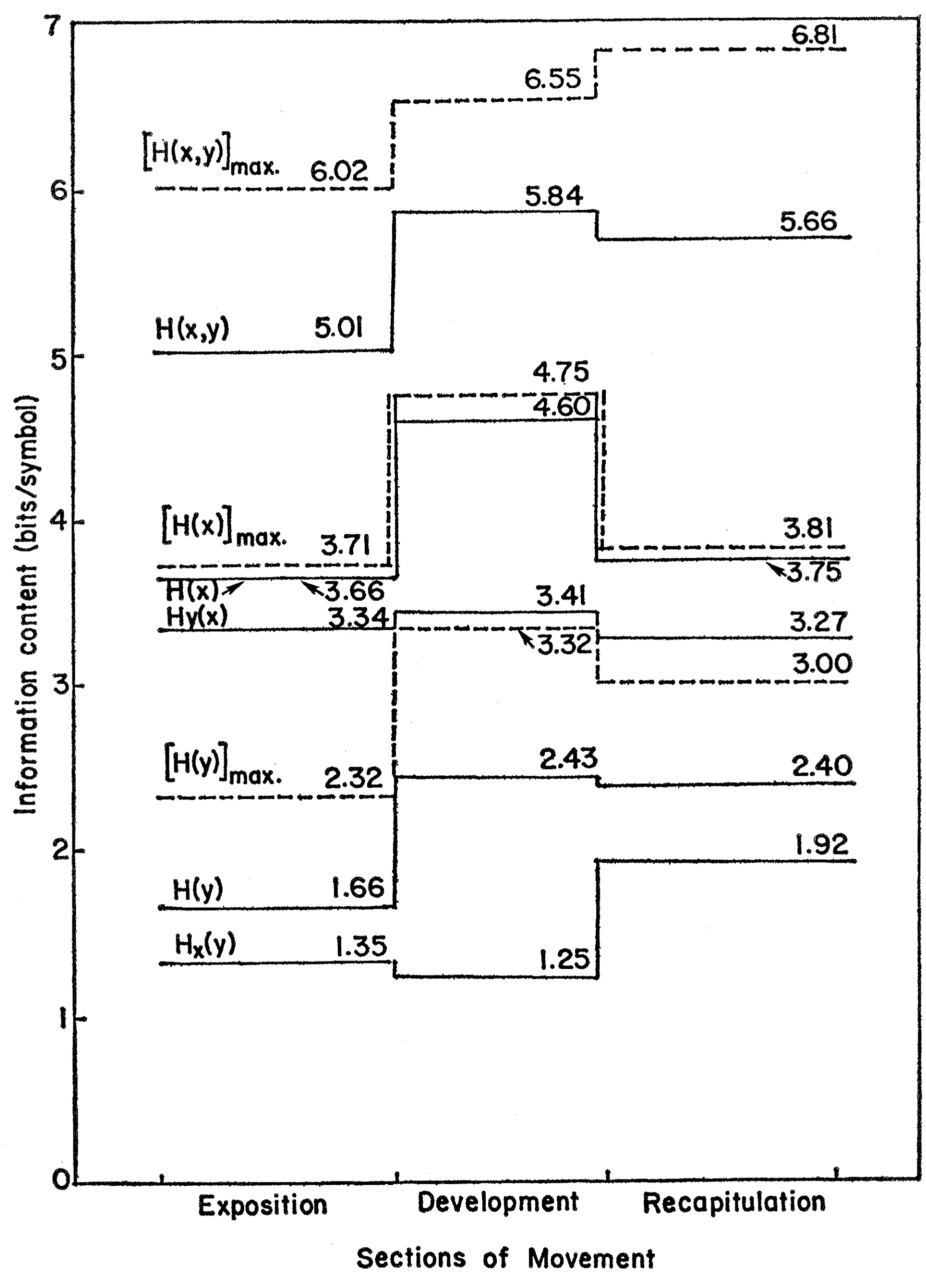

Fig. 4. Information contents, in bits per symbol, computed for pitch and rhythm in the first movement of Anton Webern's *Symphonie-Opus 21.*

Compared to digital computers, analog systems have certain advantages which can be exploited in some investigations of timbre. (i) In synthesizing sounds, several parameters can be easily varied manually by an operator to achieve a preconceived timbre. (ii) With a relatively low-cost analog machine, large amounts of time can be committed to the research, whereas a general-purpose digital computer used by many people is ordinarily available to each person for only a short time each day. (iii) Individuals usually find analog systems easier to work with than digital systems, because they are normally simpler to operate and to understand.

An analysis problem which can be handled effectively by an analog system, for example, is the analysis of a transient harmonic tone. An advantage of the analog system is the relative cheapness of the sharp cutoff filters needed to achieve both maximum discrimination between harmonic frequencies and the greatest accuracy in retrieving the tonal envelopes of the individual harmonics.

In applying digital techniques, on the other hand, we record tones of the musical instrument on magnetic tape under carefully controlled "dead" conditions or, alternatively, under concert-hall conditions. We can then play the recorded tones into the ILLIAC II computer via an A/D converter, store and analyze the raw data, and finally print out the analytical results. The feasibility of doing this for both the steady-state and the transient components of a variety of instrumental tones has been recently demonstrated by Freedman (*15*).

Computer synthesis of musical-instrument tones. Such analyses can be tested for completeness by synthesizing sounds via a D/A converter in accord with the extracted data. Moreover, one or more of the parameters can be mathematically simplified (perhaps to the point of being set equal to zero) until one or another of the following conditions occur, as determined in subjective listening tests. (i) The sounds can be recognized as resulting from analysis of the original instrument (the condition called "recognizable"). (ii) The sounds seem to be a "good" reconstruction of the original ("appreciable"). (iii) The sounds cannot be distinguished from the original ("nondistinguishable").

Computer synthesis of "postulated" sounds. Our third approach centers on the study of effects produced by a priori variations in (i) frequency spectra distributions, (ii) the growth and decay of individual frequency components with respect to time, and (iii) the rates and types of amplitude and frequency modulations. By synthesizing tests, we expect to discover totally new timbres and to develop broad categories which will contain conventional sounds as well. This project should provide new data on perception in hearing as well as valuable data for composers working in the electronic-music medium.

Studies of Complex Musical Structures

That isolated sounds taken singly do not convey much musical information is a truism. It is the ways in which such sounds are combined into larger patterns according to various "rules of the game" that determine the sense of audible messages. In spoken or written language, for example, the sense of a message depends not only on what symbols—what words, stresses, punctuation, and so on—are chosen but also on the sequences used to organize these symbols into relatively complex structures. In effect, appropriate relationships have been developed between content and form that vary from, for example, standard scientific prose, where the information conveyed depends largely on *what* is said, to poetic language, where much more depends on *how* it is said.

Music, like language, is one of the basic forms of human communication, and it possesses all of the important attributes of language. But it does not necessarily possess them in the same proportions. For example, music is used to a far lesser extent than language to deal with topics other than itself: it is minimally discursive. On the other hand, its structure is more complex than that of language, so much so that the information rate of a typical musical message almost certainly exceeds that of a typical verbal message. We discovered an interesting instance of this when we programmed for a computer the music notation derived from the music typewriter. We soon realized that ordinary music notation is really quite compact and efficient in terms of binary numbers—that is, in terms of bits of information per page of score. In general, music ought to be an ideal abstract material for the analysis of language structure. Conversely, investigation of the ways in which musical structures are synthesized in a computer should provide clues to the mechanisms by means of which human intelligence deals with language structure. We are thus working with aspects of learning theory and with models of thought processes.

During the past several years we have developed at the University of Illinois a number of research studies to explore the possibilities of using digital computers in this general line of investigation. Many of these studies have been described in recent publications (*20*). A number of similar, con-

Fig. 5. The opening bars of a computer-generated musical composition, *Sonoriferous Loops*, by Herbert Brün.

current publications by other investigators have also begun to appear (*21*). The following seem to be the most important topics being studied.

Statistical analyses of existing musical structures. The process employed at the University of Illinois for making such analyses is, first, to count the occurrences, in existing music, of pitches, durations, timbres, intensities, and the like, and, second, to compute transition frequencies for all possible combinations of these parameters. Because the number of possible stochastic sequences is enormous, a computer is required for detailed calculations. The results of the computations are conveniently interpreted in terms of information theory concepts, like entropy and redundancy.

We have already completed several studies along this line, choosing simple and straightforward stochastic models for frequency counts. As a typical example of the results so far obtained, we show in Fig. 4 a plot of information contents, in bits per symbol, computed for the first movement of Anton Webern's *Symphonie-Opus 21*, a well-known recent composition written in 12-tone style. Here we plot values such as $H(x)$ for the first-order pitch structure, $H(y)$ for the first-order rhythmic structure, $H_y(x)$ for the second-order pitch structure as it depends on rhythmic structure, and $H_x(y)$ for the second-order rhythmic structure as it depends on pitch structure. This and similar results are discussed fully elsewhere (*22*).

In general, our conclusions thus far suggest that simple stochastic models of music are not sufficient beyond fourth- or fifth-order conditional frequencies. Therefore, we think it is necessary next to analyze music in terms of a more complex model which involves what we call a "hierarchial structure." We suggest that a musical message (and, in fact, any language structure) is built up in terms of (i) major points of articulation that depend more or less directly one upon the other, and (ii) lesser components that serve as interstices in this primary network.

Computer synthesis of music structures. As explained elsewhere (*23*), the programmer of computer music must recognize at least three types of basic constraints upon his programming ideas: (i) a priori conditions chosen by the programmer; (ii) conditions developed from statistical analyses; and (iii) self-generated conditions developed by the computer itself as a consequence of initial conditions. These conditions, singly or collectively, can be employed to generate patterns for studies that range from small and systematically planned tests to large-scale, complex experiments in which many factors operate to correlate the components of the whole. First, a priori conditions can be developed from well-known, historically based compositional procedures, from reasoned judgments on the part of the programmer, or from systematic or even arbitrary variations of constraints thought possibly to be significant. All such conditions serve to reduce the information associated with zero-order random sequences such that it may not necessarily be uniformly distributed over the whole symbolic sequence being generated. Second, statistical data can be used for synthesis, not only as a direct test of the analytical procedures by means of which such data were obtained but also as sources for probability tables for building up component sections in a complex structure, which can then be inspected and evaluated. Third, in communication, self-generating processes are, presumably, based on more complex controlling factors. In particular, many ordinary messages seem not to be structured solely in terms of already established constraints; rather, the constraints are gradually imposed and altered as the effects of initial conditions are felt. In general, it appears that this type of programming would more nearly approximate conceptual processes that occur when a message is being thought through and composed. Heuristic programming of this type is one area we wish to explore.

At present, at the University of Illinois, we are developing a completely generalized programming language for musical composition that is written in SCATRE for IBM-7094-type computers—that is to say, essentially in simple machine language, since SCATRE is but a set of slightly modified mnemonic representations of basic computer instructions. This music programming language we have called MUSICOMP (*mu*sic-*s*imulator-*i*nterpreter for *com*positional *p*rocedures). MUSICOMP can be learned without too much difficulty by composers, since it employs whenever possible appropriate mnemonic representations of music notation and vocabulary.

Thus far, we have completed two new compositions by means of MUSICOMP. The first was written by Hiller in collaboration with Robert Baker. It is entitled *Computer Cantata* and consists of a series of studies of (i) rhythmic pattern generation, (ii) totally predetermined 12-tone writing, (iii) composition in tempered scales of nine to 15 tones per octave, and (iv) five successive stochastic approximations, from zero order to fourth order, to known examples of English text and a particular contemporary style of composition (*24*). The score of this cantata is also being published (*25*). More recently, Herbert Brün has completed a composition entitled *Sonoriferous Loops*, which extends some of the techniques applied in the *Computer Cantata*. A short excerpt of the score is shown in Fig. 5. Since neither of these compositions comes to grips with many essential factors relating to large-scale musical structure—that is, the hierarchical structure referred to above—it is now planned to write numerous subroutines to MUSICOMP which will extend its usefulness.

Computer synthesis of sound patterns. The most important extension of simple studies of computer synthesis of sound is the study of synthesis of systematically varied sound structures made up of simpler elements. Many possible studies of this type come immediately to mind. The following are some areas that should be investigated. (i) The perception of the simultaneous sounding of single sounds. The effects produced when sounds blend together and the effects of masking should be considered. (ii) Time perception. To date, the study of speed of occurrences and groupings of sounds has been only minimally studied. We propose to extend work initiated in our studio several years ago (*26*), using equipment superior to that originally available. (iii) The synthesis of small phrase structures in which acoustic variables are systematically permuted. (iv) The effect of random variables on the identification of timbres in a sound complex.

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Status of the National Standards for Physical Measurement

Progress in science and technology requires a highly developed measurement system of national scope.

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The Institute for Basic Standards (IBS), one of four institutes which comprise the National Bureau of Standards, has the responsibility within the federal government of providing "the central national basis for a complete, consistent system of physical measurement properly coordinated with those of other nations."

Implicit in the assignment of this responsibility is recognition that there exists in fact a national system of measurement and that this system is a centralized one, with a central laboratory which develops and maintains the national standards (*1*) for physical measurement and provides the starting point for a chain of measurement leading from these standards to the ultimate users of the system. This chain must provide for measurements of all necessary magnitudes, from the properties of atoms to those of the universe.

From the point of view of the ultimate user who faces a measurement problem, such as finding the diameter of a ball bearing or the melting point of a metal, the measurement chain can operate in two different ways. (i) It can provide the user with a calibrated instrument, traceable back to the national standards, with which he can measure the diameter or the melting temperature. (ii) In the case of the melting temperature or other, similar properties, it can provide him with an immediately available answer in the form of critically evaluated data which previous investigators have obtained in measurements based on the national standards, so that he does not need to make the measurement himself.

As the nation's central measurement laboratory, the National Bureau of Standards exercises leadership in both these measurement areas. In the Bureau's laboratories the acquisition of standard reference data by precise measurement goes on side by side with research to develop and improve the national standards and associated measurement methods.

The strength and utility of the measurement system depend fundamentally upon the existence of a complete, consistent system of units and standards around which the system can develop. In IBS we are concerned with the establishment of these units by international agreement, the realization of the standards which represent them, and the development of a chain of measurement from these standards to the multiples and submultiples needed by our technologically based society. These activities, we find, offer an exciting field of technical endeavor which reaches to the frontiers of science and technology. Indeed, the state of sophistication of our measurement system is an important gage of the scope and utility of our science and technology. Let us look more closely at this system and at the units upon which it is based.

Our national measurement system is part of an international system used by all leading nations of the world, and is the result of a worldwide progression toward increasing sophistication of measurement, both in concepts and in application. This international system has its basis in the metric system of weights and measures, originally devised by a committee of the French Academy in 1791. An Act of Congress in 1866 made the metric system legal, though not mandatory, in the United States. In 1875 the United States joined with 16 other principal nations of the world in signing the Treaty of the Meter. This treaty provided for the establishment of an International Bureau of Weights and Measures to be situated near Paris, and an International Conference of Weights and

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