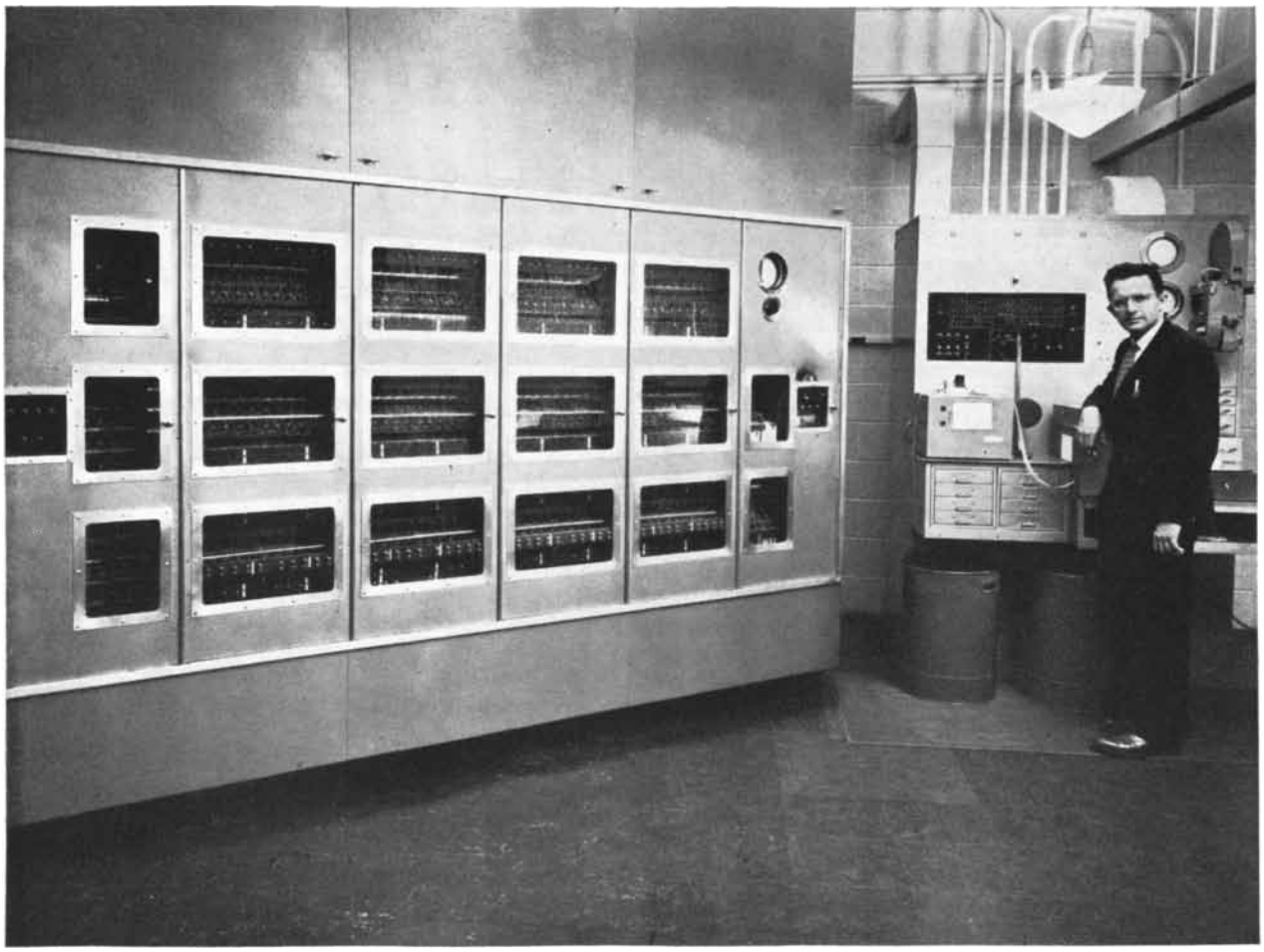
COMPUTER MUSIC

Information theory makes possible the programming of a computer to compose music. The process by which the machine does so throws light on musical structure and on the methods of human composers

by Lejaren A. Hiller, Jr.

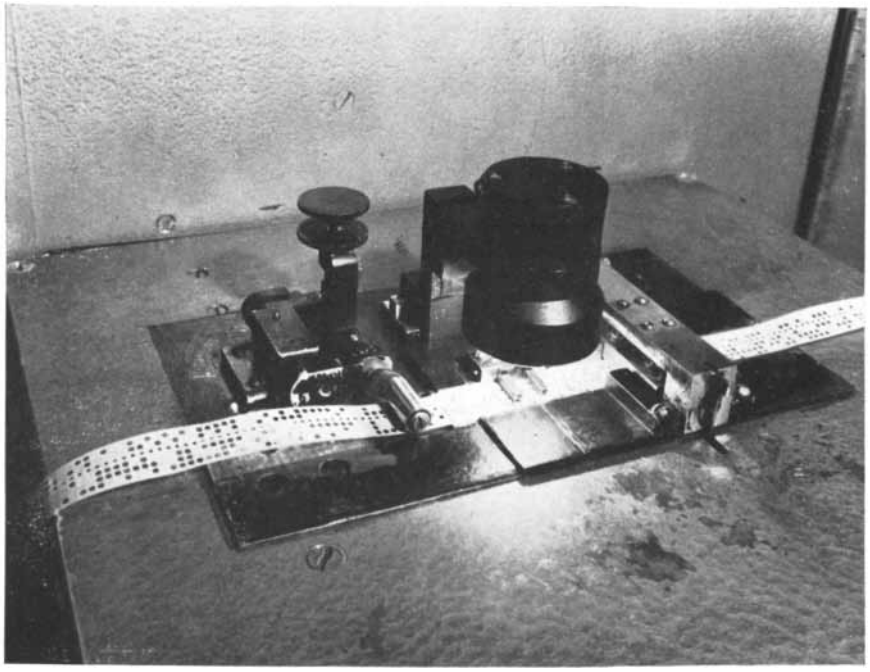
Can a computer be used to compose a symphony? As one who has been engaged in programming a large digital computer to produce original musical compositions, I can testify that the very idea excites incredulity and indignation in many quarters. Such response in part reflects the extreme view of the 19th-century romantic tradition that regards music as direct communication of emotion from composer to listener—"from heart to heart," as Wagner said. In deference to this view it must be conceded that we do not yet understand the subjective aspect of musical communication well enough to study it in precise terms. The appreciation of music involves not only psychological needs and responses but meanings imported into the musical experience by reference to its cultural context. On the

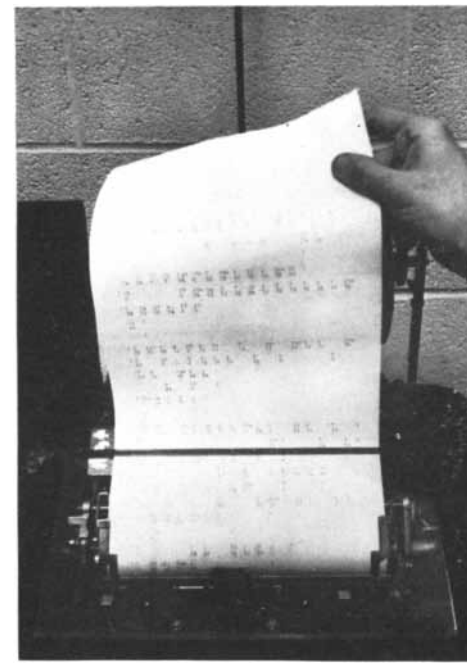


"ILLIAC" DIGITAL COMPUTER at the University of Illinois was used for the experiments in composition described in this article. It has "composed" hundreds of simple melodies as well as more complicated musical structures. At right is the author.

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COMPUTER'S MUSICAL OUTPUT is punched into paper tape shown at left, which is then run through a teletype machine to produce sheets of letter-number combinations (*center*). These are then decoded by hand into conventional musical notation (*right*).

other hand, music does have its objective side. This can be defined as existing in the score as such, quite apart from the composer and the listener. The information encoded there relates to such quantitative entities as pitch and time, and is therefore accessible to rational and ultimately mathematical analysis.

In recent years the "physics of music" has disclosed much that is mathematical in music. It reveals how sound waves are formed and propagated, how strings, membranes and air columns vibrate and how timbre depends upon complex wave-structure; it has provided universal standards of frequency and intensity, and clarified the rationale of musical scales. In its most compact form, acoustics reduces the definition of musical sound to a plot of wave-form amplitude versus time. The groove of a phonograph record, for example, contains only this information and yet yields a believable reconstruction of an original musical sound.

Acoustics, however, deals primarily with isolated elements of music and has thus far said relatively little about how these elements may be combined in a musical composition. Musicians have devised various nonmathematical systems for analyzing the structure of compositions. More recently they have begun to draw upon a new branch of applied mathematics known as information theory as a means of clarifying this aspect of musical communication.

Information theory relates the "information content" of a sequence of symbols (be they letters of the alphabet or musical notes) to the number of possible choices among the symbols. Information content thus resembles entropy or the degree of disorder in a physical system. The most random sequence has the highest information content; the least random (or most redundant) has the lowest. The apparent paradox in this statement derives from the definition given the term "information" in the theory. As Warren Weaver has observed, the term "relates not so much to what you *do* say as to what you *could* say" [see "The Mathematics of Communication," by Warren Weaver; SCIENTIFIC AMERICAN, July, 1949]. Information in this sense is not the same thing as meaning, and information theory is concerned more with the reliability of communication systems than it is with problems of meaning. Thus, it can be seen, the general inquiry into communication is confronted with the same dualistic question of form and meaning that faces the study of musical communication. Weaver encourages us to believe, however, that information theory has cleared the way toward "a real theory of meaning."
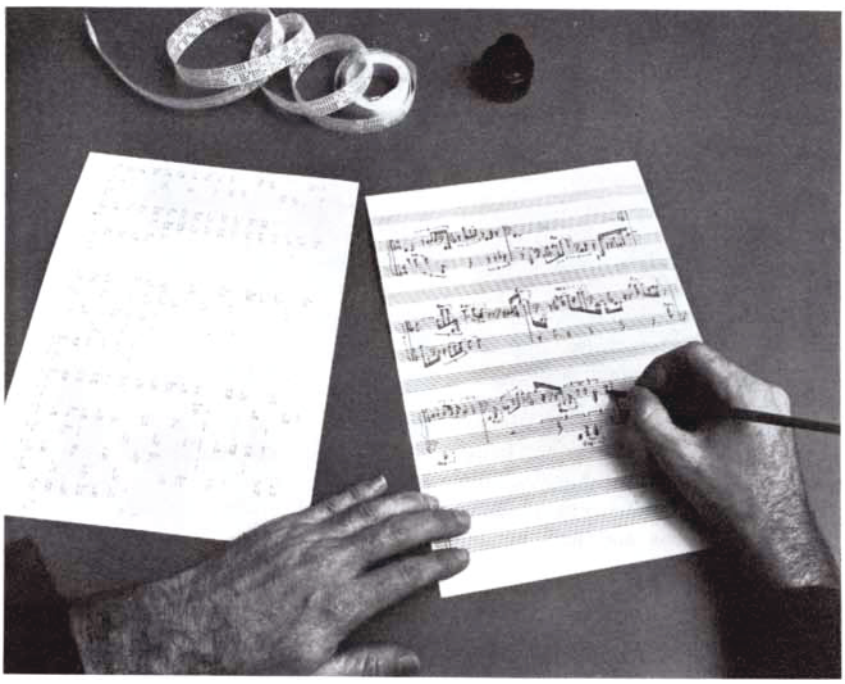
Music, sometimes defined as a compromise between chaos and monotony, appears to the information theorist as an ordered disorder lying somewhere between complete randomness and complete redundancy. This viewpoint accords well with much of traditional musical esthetics. As early as the fourth century B. C. the Greek writer Aristoxenus noted that "the voice . . . does not place the [musical] intervals at random, . . . for it is not every collocation but only certain collocations . . . that distinguish the melodious from the unmelodious." The composer, employing what Stravinsky has called "the great technique of selection," introduces redundancy into his relatively random materials in order to organize them into a "meaningful" pattern.

To be sure, meaning is as difficult to define in music as it is in every other kind of communication. But musical sounds are not, as words are, primarily symbols of something else; the meaning of music is peculiarly dependent upon its own structures as such. The study of musical structures by information theory should open the way to a deeper understanding of the esthetic basis of composition. We may be able to respond to Stravinsky's injunction and cease "tormenting [the composer] with the *why* instead of seeking for itself the *how* and thus establish the reasons for his failure or success."

From the analytical standpoint, the esthetic content of music can be treated in terms of fluctuations between the two extremes of total randomness and total redundancy. The significant fluctuations manifest themselves not only between one composition and another but also among elements or sections of the same

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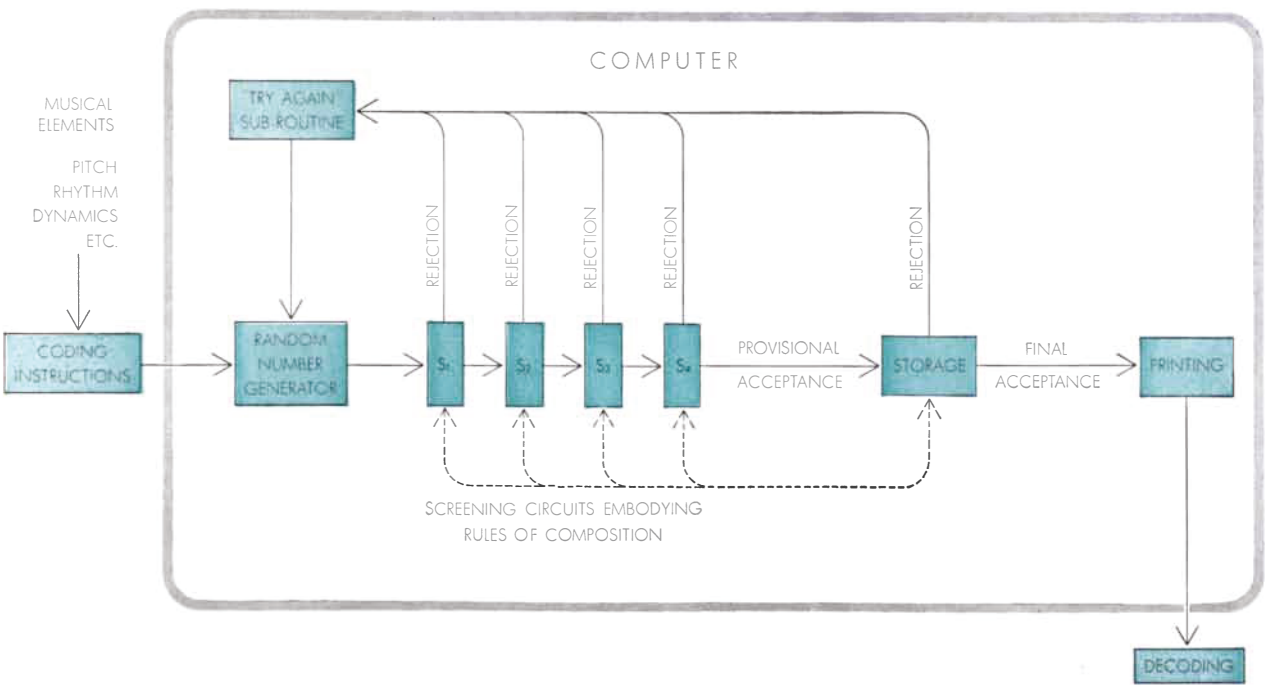
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Future experiments may develop a method for automatic decoding and printing. Music publishers, who now use much expensive hand labor, would welcome such a technique.

composition. To take a very simple example, the "dominant 7th" chord GBDF is highly redundant under the rules of conventional harmony, because it will most frequently be followed by the chord CEG. The "diminished 7th" chord G♯ BDF, by contrast, is far less redundant, for it can be followed with equal probability by any one of a dozen-odd chords. Or consider the "sonata form" of organization which classical composers typically employed for the first movements of their longer compositions. In this musical structure the "exposition," in which the composer sets forth the themes, is fairly redundant (that is, predictable); the "recapitulation," in which he restates them, is even more so. The intervening "development," in which the themes are broken up, recombined and shifted through a number of keys, is far less redundant than either. As a final example, the stylistic device of modulation (key-shift) shows a fairly steady decrease in redundancy over the past 200 years. Mozart employed a limited number of rather standardized modulations. In Chopin and Brahms the modulations are more extreme and occur more frequently and less predictably. Wagner and Debussy modulate so freely that the listener often loses any immediate and unequivocal sense of key. Many modern composers have abandoned the concepts of key and modulation altogether and in this dimension approach complete randomness.

By standards such as these it is possible, at least in theory, to construct tables of probabilities describing a musical style, such as Baroque, Classical or Romantic, and perhaps even the style of an individual composer. Given such tables, one could then reverse the process and compose music in a given style. The task of composition would start from the random condition with choices among musical elements all equally probable. The introduction of redundancy in accord-



COMPUTER "COMPOSES" by a process of which the general features are here shown schematically. The machine generates random integers which are then screened by computational circuits that are arithmetical analogues of rules of composition. If circuits reject an integer, the "try again" circuit automatically produces a new one. Integers accepted by the screening circuits are stored in the memory until the composition is complete; memory and screening circuits are joined by feedback linkages symbolized by broken arrows. If the machine cannot complete a sequence without breaking the rules, it clears its memory and begins anew.

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ance with a particular scheme of probabilities would extract order from chaos. It is not to be thought, however, that order is the sole criterion of beauty; as the musicologist Leonard B. Meyer has observed, "Some of the greatest music is great precisely because the composer has not feared to let his music tremble on the brink of chaos."

A few years ago Richard C. Pinkerton of the University of Florida employed this method to produce a simple "tune maker." He derived his probability tables by averaging the probabilities in a collection of nursery tunes [see "Information Theory and Melody," by Richard C. Pinkerton; SCIENTIFIC AMERICAN, February, 1956]. As he noted, however, this method produces only banal tunes. If more interesting music is desired, criteria other than simple averages must determine the probabilities.
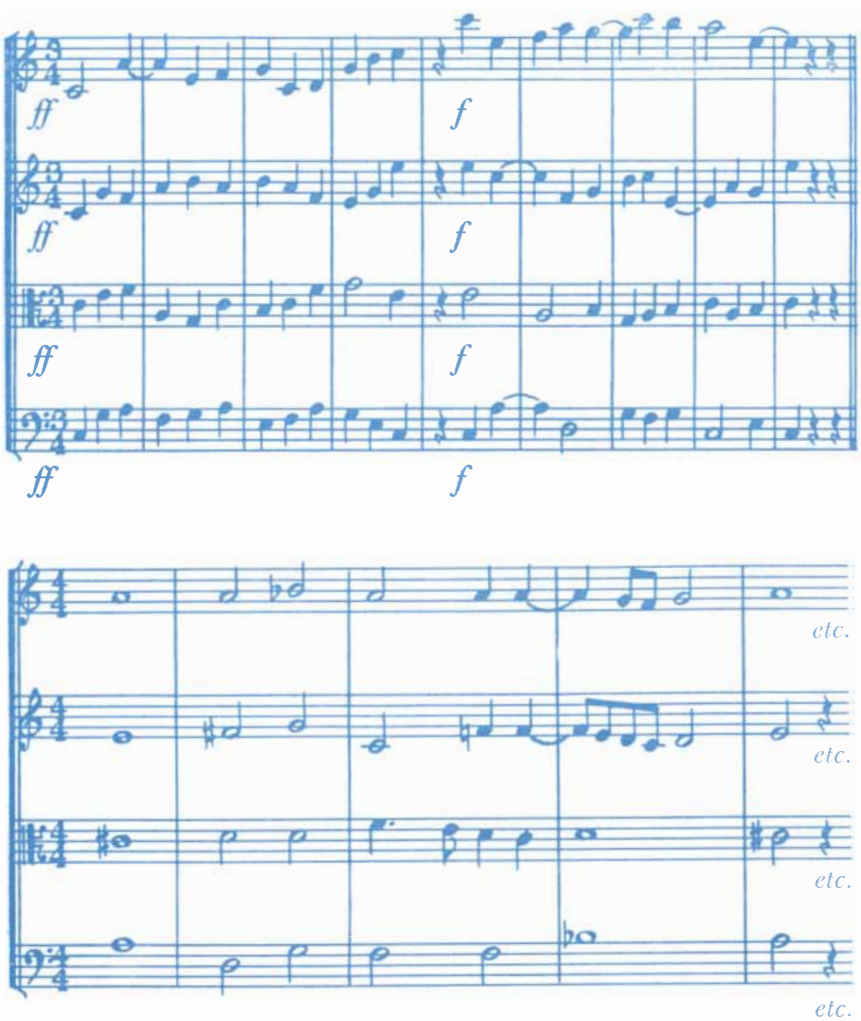
A number of composers, both classical and contemporary, have produced more sophisticated musical structures embodying mathematical or quasi-mathematical "programs" that reflect an explicit concern with order and disorder. Especially illuminating are the extreme types of such structures: random music and totally organized music.

In its literal sense, pure random music is equivalent to "white noise"—the undifferentiated hissing sound made up of all possible audible frequencies occurring at random time intervals. It can be "composed" on any good high-fidelity set simply by turning the volume control high and thereby amplifying the random motions of electrons and ions in the tubes. At the opposite pole, the unvarying dial tone of a telephone provides a good example of totally organized music. Obviously neither extreme has much to offer the listener. To obtain sufficient variation in texture the composer must move away at least a little from total randomness or total redundancy.

Perhaps the simplest method of composing "almost random" music is to spatter ink from a brush on a page of blank music paper. By adding stems to the spots and then selecting the meters of successive measures by picking cards from a deck, one obtains random music that is sometimes playable if not harmonious [*see illustration on opposite page*]. A second and rather well-known example of chance music is Mozart's "A Musical Dice Game." This piece, one of many similar "compositions" produced as parlor games in the late 18th century, consists essentially of several dozen assorted measures of music, the order of which is determined by rolling dice. A more modern random work, "Imaginary Landscape" by the American composer John Cage, is "scored" for 12 radios and thus derives a strong element of randomness from regional and temporal variations in radio programs. Moreover, the score itself, which specifies the tuning of each radio and changes in volume, is based on chance numbers derived from an ancient Chinese book of oracles. Cage composes by several other chance methods, including "the observations of imperfections in the paper on which I happen to be writing" and the random shuffling of score pages just before performance.

John R. Pierce of Bell Telephone Laboratories, an authority on information theory, has demonstrated other approaches to the composition of simple "probability music." In one, a sequence of chords is chosen by means of dice rolls and a table of random numbers; in another, a series of volunteers each contributes a measure. A number of European composers have produced more elaborate random music electronically by causing random sequences of electrical signals to trigger sequences of tones.
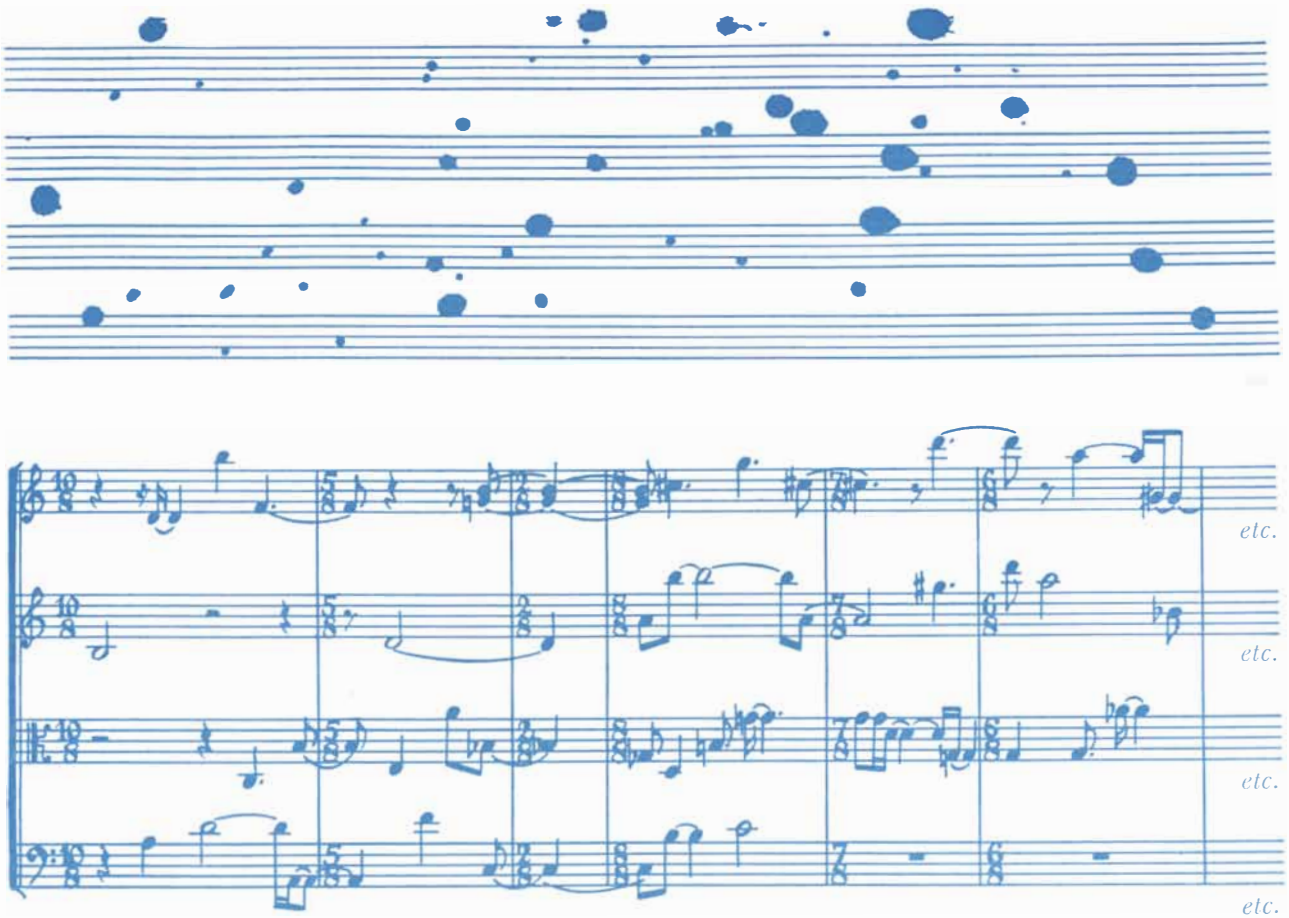
Like random music, highly organized music does not lack historical precedent. A notable example is the "isorrhythmic" music of the 14th and 15th centuries, which was based on abstract formulations that took precedence over conventional rules of harmony. Among contemporary composers, Cage has produced what is probably the most perfect example of the genre in his composition "4:44," which consists of four minutes



"FIRST SPECIES COUNTERPOINT" composed by ILLIAC (*top*) is compared with a portion of the motet "Adoramus Te Christe," composed in the same style by Palestrina (*bottom*). The computer produced monotonous rhythms here because its program contained no provision for varying rhythms until later experiments. The computer music is taken from "Illiac Suite for String Quartet," by Lejaren A. Hiller, Jr., and L. M. Isaacson. Copyright 1957 by New Music Editions; assigned to Theodore Presser Company, 1959.

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RANDOM MUSIC can be "composed" by spattering ink from a brush onto blank music paper (*top*). When the spots are transcribed (*bottom*), the horizontal distance between them defines their time value. Meters are obtained by drawing cards from a deck.

and 44 seconds of silence. Other contemporary composers have produced less totally organized but more audible pieces by composing according to invariant sequences of numbers. Each number is associated with musical elements such as pitch, rhythm, dynamics and orchestration. This method of composing evolved out of Arnold Schönberg's 12-tone technique. Once belabored as rigid and ultra-mathematical, Schönberg's works seem hardly "programmed" at all when compared with those of his "descendants." Karlheinz Stockhausen's "Zeitmasse" is an example of recent programmed music available on phonograph records. Its elaborately organized structure is not readily discernible by ear alone, so that it does not sound very different from the general run of modern compositions.

The concept of mathematically programmed music easily leads to the notion of composition by computer. In 1955 Leonard M. Isaacson and I began a series of experiments in composition with ILLIAC, the high-speed digital computer at the University of Illinois. In due course we completed four groups of experiments, the results of which we have sampled in the "Illiac Suite for String Quartet."

As our first step we set the computer to composing simple melodies. To this end we programmed the machine to generate random integers by a technique borrowed from the "Monte Carlo" method, which physicists have devised to solve certain problems involving multiple probabilities. Random integers from 0 to 14 represented the tones ("white notes" only; no sharps or flats) in a two-octave range of the C-major scale. To introduce redundancy we screened the integers by feeding in additional programming instructions; these embodied arithmetical analogues of rules of composition governing "permissible" sequences of notes. We selected the rules from the elaborate injunctions for "strict first-species counterpoint," a formalized musical idiom based on the methods of such 16th-century composers as Palestrina.

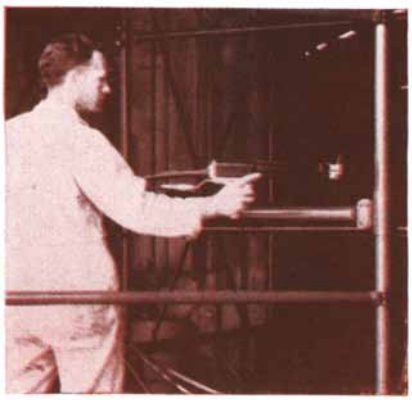
Integers that passed the screening procedure were stored in the computer's "memory" until the machine had completed a melody by returning to C, the note with which it had begun. The complete melody was then printed on perforated tape, from which it could be transcribed into conventional musical notation [*see illustrations at top of pages 110 and 111*]. Rejection of an integer automatically triggered a "try again" program that generated a new integer. The machine continued "trying" until it produced a satisfactory note or until it "concluded" (after 50 unsuccessful trials) that no such note existed, that is, it had "written itself into a corner," as human composers sometimes do. In the latter case it cleared the incomplete melody from its memory and began afresh from C.

In the course of an hour's operation the machine produced several hundred melodies from three to 12 notes long. It was then programmed to produce two-voice counterpoint—two melodies at once—incorporating for this purpose four more instructions that screened out dissonances between the voices. The addition of still other instructions enabled

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the machine to produce four-voice counterpoint. The more elaborate programs produced more trials and "erasures," but the machine still composed copiously.

For our second experiment we devised additional screening instructions embodying the entire set of 14 rules of strict first-species counterpoint. The machine was first set to turning out random "white-note" music in four voices; randomness was then made to yield to redundancy in small increments by feeding in the screening instructions one by one. The complete set of instructions yielded counterpoint of fair quality, strongly reminiscent, if one ignores a certain monotony in rhythm, of passages from Palestrina.

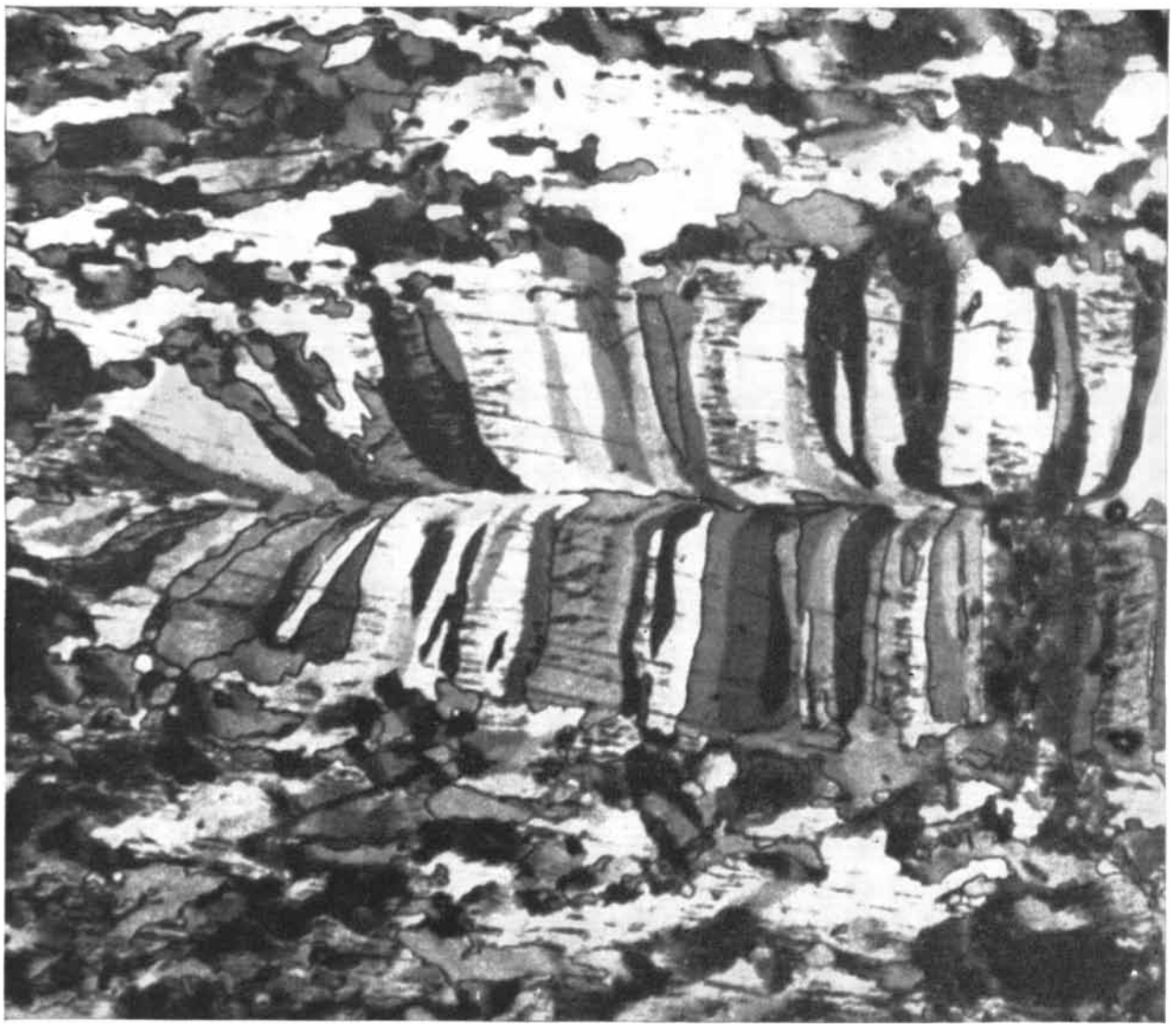
In Experiment III we sought to find ways of producing the rhythmic and

CLOSED RHYTHMS	OPEN RHYTHMS	BINARY NUMBER	DECIMAL NUMBER
		0000	0
		0001	1
		0010	2
		0011	3
		0100	4
		0101	5
		0110	6
		0111	7
		1000	8
		1001	9
		1010	10
		1011	11
		1100	12
		1101	13
		1110	14
		1111	15

RHYTHMIC CODING for the computer is based on 4/8 meter (chosen arbitrarily) with the eighth-note as the smallest rhythmic unit. All rhythms possible under these restrictions can be expressed as binary numbers equivalent to the decimal numbers from 0 to 15. Random choice determines the order of rhythmic patterns and selects "closed" or "open" form.

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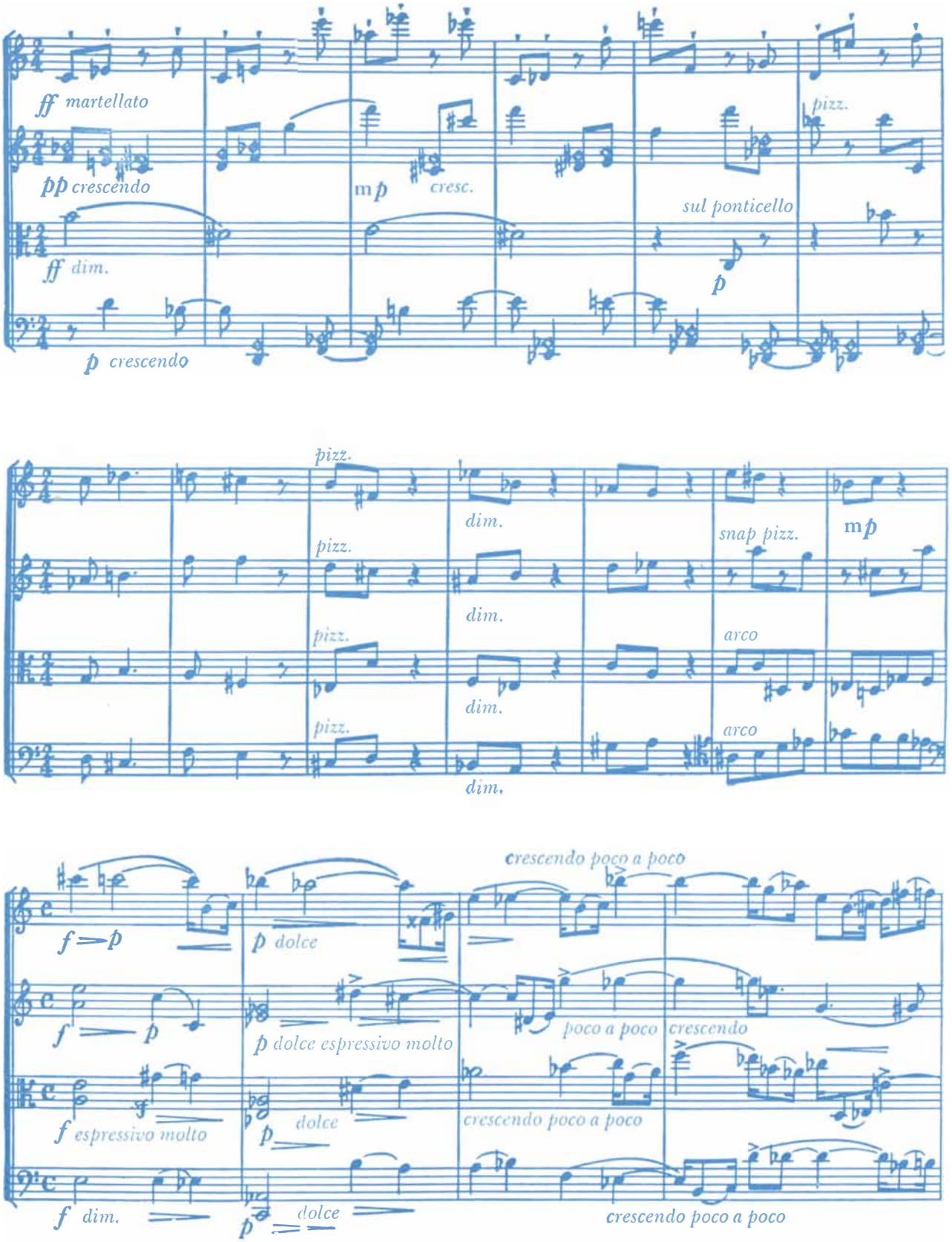
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RANDOM CHROMATIC MUSIC produced by the computer (*top*) resembles the compositions of some extreme modern composers. The introduction of redundancy in melody, rhythm and playing instructions produces a more ordered texture (*middle*) that suggests passages from Bartok. Samples of computer music from "Illiac Suite," Copyright 1957, New Music Editions; assigned to Theodore Presser Company, 1959. Shown below is a passage from the first movement of Bartok's "First String Quartet." Copyright 1929 by Universal Editions; renewed 1956. Copyright and renewal assigned to Boosey and Hawkes Inc. Reproduced by permission.

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dynamic variety that the earlier compositions lacked. A simple method gave us a considerable variety of rhythm. With 4/8 time as the meter and the eighth-note as the smallest rhythmic unit, all the rhythmic patterns possible under these restrictions were coded in binary digits (that is, numbers expressed by 1 and 0, representing the "on" and "off" positions of a relay). Thus 1111 represented four eighth-notes; 1110, two eighth-notes followed by a quarter-note; 1010, two quarter-notes, and so on. The resulting series of permutations formed a sequence of binary numbers equivalent to the decimal numbers 0 to 15 [*see illustration on page 114*]. Since rhythms in music do not normally shift with every measure, rhythmic redundancy was introduced by a second series of random numbers that programmed the machine to repeat a particular rhythm up to 12 times. To this "horizontal" redundancy in the melodic line of the individual voices another binary code added "vertical" redundancy among the four voices. Here 0000 indicated that all four voices would be rhythmically independent, 1111 called for the same rhythm in all voices, and so on. Similar methods introduced patterns of dynamics (*forte, crescendo*, and so on) and variations in playing instructions (*legato, tremolo, pizzicato*, and so on).

Since the object was to produce a type of music less imitative than strict counterpoint, the machine was first permitted to write entirely random chromatic music (including all sharps and flats). The result was music of the highest possible entropy content in terms of note selection on the chromatic scale, and thus it was strongly dissonant. With the minimal redundancy imposed by feeding in only four of the 14 screening instructions, the character of the composition changed drastically. While the wholly random sections resembled the more extreme efforts of *avant garde* modern composers, the later, more redundant portions recalled passages from, say, a Bartok string quartet [*see illustration on opposite page*]. The experiment concluded with some exploratory studies in Schönberg's 12-tone technique and similar compositional devices.

Experiments II and III thus developed the contrasts between two widely different styles, that of the 17th and that of the 20th century. One style is highly restrictive and highly consonant but sounds quite simple; the other sounds dissonant, much more complex and difficult to decipher. The contrast underlines an important musical moral: Simplicity of style and hence accessibility

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$$1-p = \frac{1}{\xi_2 \Sigma_{S2} t_2} \int_{resonance} \frac{\alpha(u)}{1 + c\,\alpha(u)}\, du$$
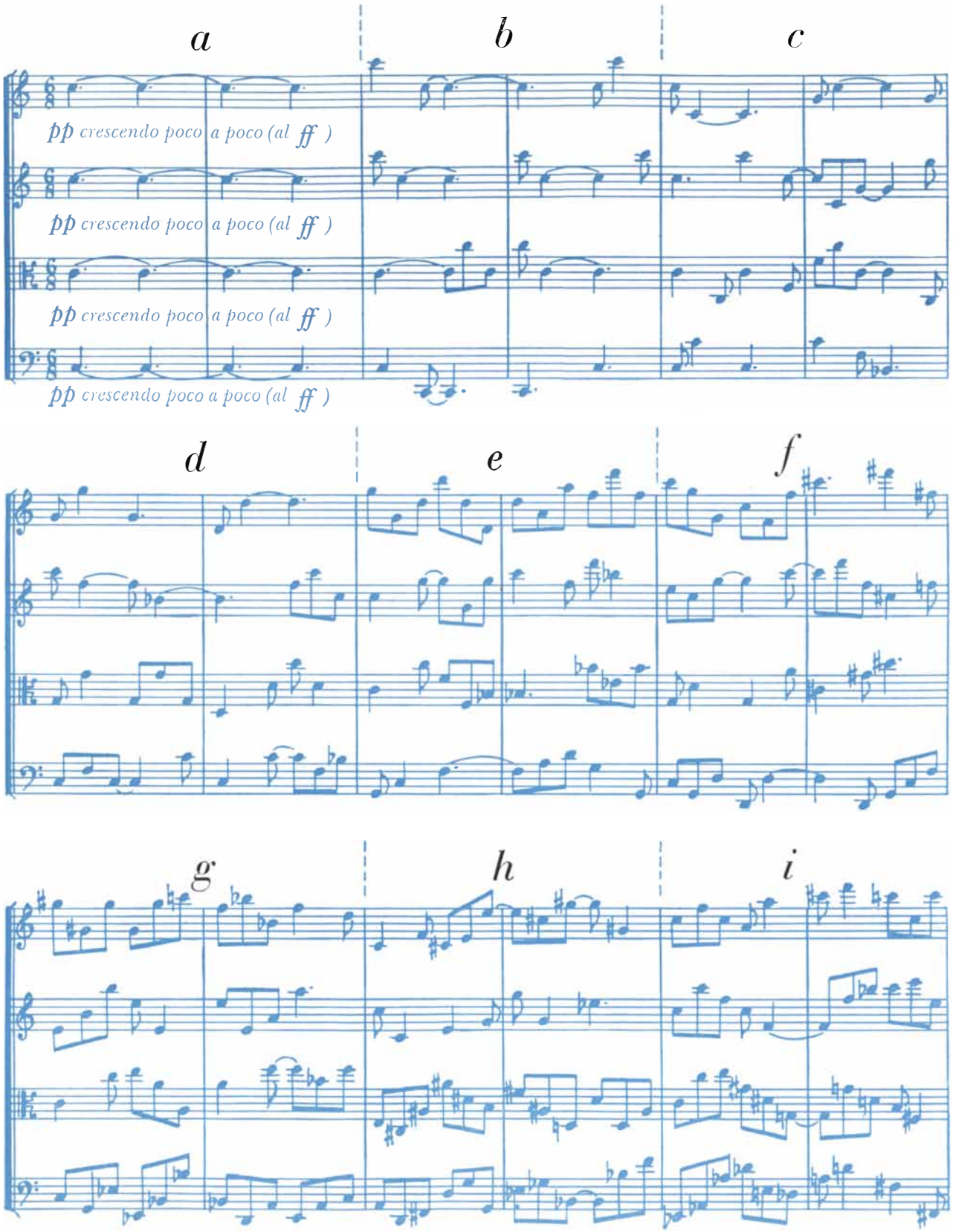
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"MARKOFF CHAIN" MUSIC is composed by selecting intervals between successive notes according to a shifting table of probabilities. During the first two bars, the probability of unison (the "zero" interval) is 1; that of all other intervals, 0. The music necessarily remains on the same note. After each two bars the probabilities shift according to the scheme shown on page 120. From Experiment IV of "Illiac Suite for String Quartet," copyright 1957, New Music Editions; assigned to Theodore Presser Company, 1959.

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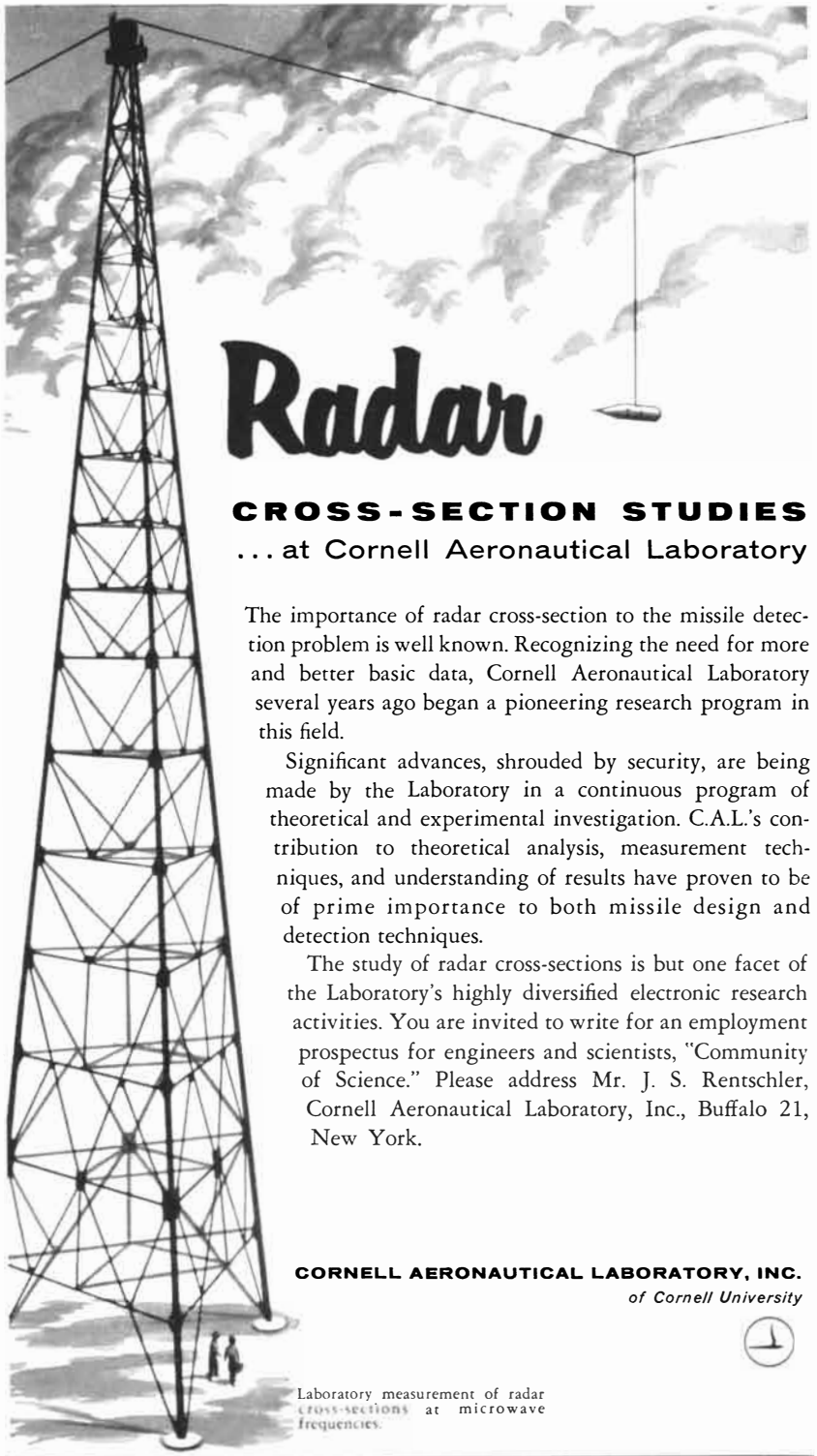
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bear an inverse relationship to freedom of choice. The simpler the style, the more severe the restrictions and the higher the degree of redundancy. By the same token, music that sounds simple may well be more difficult to write. In the freer style the difficulty involved in making the best choices among the larger number of alternatives is offset by the fact that more of the available alternatives are permissible. Each choice, in other words, is less significant to the total effect.

In Experiment IV the objective was the synthesis of music from purely mathematical rules—a style of composition peculiarly appropriate to a computer. To this end the computer was programmed to select the intervals between successive notes according to a table of probabilities instead of at random. Moreover, the probabilities themselves were made to shift in accordance with so-called Markoff probability chains. For example, in the first specimen of this music the "zero" interval (unison) had an initial "weight" of one while all the other intervals had a weight of zero. All voices perforce remained on the same note. After two bars the octave interval was given the weight of one and the weight of unison increased to two (unison was thus twice as probable as the octave). The fifth was the next interval added, and the respective weights of the three intervals, in order of appearance, became three, two and one. Two bars later the fourth interval was added with weights of four, three, two and one now assigned, and so on until all possible intervals had been added [*see illustrations on opposite page and on next page*].

When the computer had composed under the instruction of a number of similar Markoff programs, the probabilities were programmed to depend partly upon the last choices made. Thus if the last interval was a fifth, the probability of that interval would drop sharply and the probabilities of the others would rise. Another rearrangement linked the choice of interval to the opening note of the sequence. This latter relationship is of particular interest because it bears on the problem of tonality, the factor in conventional music by which the notes of the scale acquire individual significance because of their relationship to the keynote. The suppression of tonality, even to the point of abandoning it completely (atonalism), constitutes perhaps the most characteristic trend in "serious" music during the past 50 years.

We discovered with interest that the sound of "tonal" Markoff music closely resembled that of the "atonal"



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... at Cornell Aeronautical Laboratory

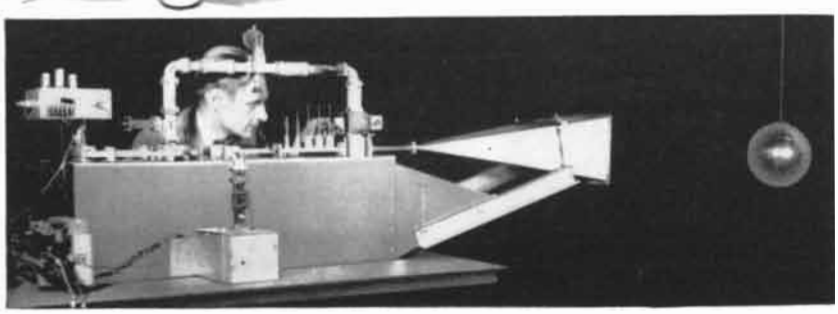
The importance of radar cross-section to the missile detection problem is well known. Recognizing the need for more and better basic data, Cornell Aeronautical Laboratory several years ago began a pioneering research program in this field.

Significant advances, shrouded by security, are being made by the Laboratory in a continuous program of theoretical and experimental investigation. C.A.L.'s contribution to theoretical analysis, measurement techniques, and understanding of results have proven to be of prime importance to both missile design and detection techniques.

The study of radar cross-sections is but one facet of the Laboratory's highly diversified electronic research activities. You are invited to write for an employment prospectus for engineers and scientists, "Community of Science." Please address Mr. J. S. Rentschler, Cornell Aeronautical Laboratory, Inc., Buffalo 21, New York.

CORNELL AERONAUTICAL LABORATORY, INC.
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Laboratory measurement of radar cross-sections at microwave frequencies.



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species, though its mathematical basis was quite different. Indeed, large sections of Experiment IV, though based on wholly abstract formulae, sounded much the same as Experiment III, which was generated under relatively unrestricted conditions. These correspondences suggest that if the structure of a composition exceeds a certain degree of complexity, it may overstep the perceptual capacities of the human ear and mind.

Since completing the "Illiac Suite," our efforts have been devoted to more complicated problems of musical structure, the solutions to which may yield a "Second Illiac Suite." As against the rather fragmentary music thus far obtained, the objective is to produce compositions in relatively lengthy conventional forms, such as theme and variation and four-part fugue. The computer will also be put to work on "totally organized" music as well as more complex Markoff chains. These and similar experiments involving a precisely specified degree and type of uncertainty should provide some quantitative criteria for judging the effect of order-disorder fluctuations in music.

A far more elaborate project is suggested by the question that began this discussion: Can a computer be used to compose a symphony? In principle, there seems to be no reason why it cannot. The computer program would have to be far more elaborate than any we have yet devised. Whether the results would justify the necessary labor is another story. With a program of reasonable length, the machine could be made to produce, say, a 42nd Mozart symphony, which would prove to be a representative but almost certainly undistinguished work. So long as the human programmer collaborates in the undertaking, the computer cannot be regarded as a truly independent composer. On the other hand, so long as the input to the computer includes some variant of the Monte Carlo method, the programmer cannot precisely specify the output of the machine. Thus the machine may be said to "compose," or at least to "improvise" within the limits set by its program.

The computer can also be used to make an original contribution to our understanding of the structure that underlies the esthetic qualities of music. As I remarked earlier, these qualities are perceived largely through the articulation of musical forms and can therefore be most fruitfully explored via the investigation of the technical problems of composition. The computer has already proved its value in this line of investigation, and in future studies we plan to explore more deeply its application to problems of musical analysis.

	a		*b*		*c*		*d*		*e*		*f*		*g*		*h*		*i*	
INTERVALS	W	P	W	P	W	P	W	P	W	P	W	P	W	P	W	P	W	P
UNISON	1	1.00	2	.67	3	.50	4	.40	5	.33	6	.29	7	.25	8	.22	9	.20
OCTAVE	0	.00	1	.33	2	.33	3	.30	4	.27	5	.24	6	.21	7	.19	8	.18
FIFTH	0	.00	0	.00	1	.17	2	.20	3	.20	4	.19	5	.18	6	.17	7	.16
FOURTH	0	.00	0	.00	0	.00	1	.10	2	.13	3	.14	4	.14	5	.14	6	.13
MAJOR 3RD	0	.00	0	.00	0	.00	0	.00	1	.07	2	.09	3	.11	4	.11	5	.11
MINOR 6TH	0	.00	0	.00	0	.00	0	.00	0	.00	1	.05	2	.07	3	.08	4	.09
MINOR 3RD	0	.00	0	.00	0	.00	0	.00	0	.00	0	.00	1	.04	2	.06	3	.07
MAJOR 6TH	0	.00	0	.00	0	.00	0	.00	0	.00	0	.00	0	.00	1	.03	2	.04
MAJOR 2ND	0	.00	0	.00	0	.00	0	.00	0	.00	0	.00	0	.00	0	.00	1	.02
MINOR 7TH	0	.00	0	.00	0	.00	0	.00	0	.00	0	.00	0	.00	0	.00	0	.00
MINOR 2ND	0	.00	0	.00	0	.00	0	.00	0	.00	0	.00	0	.00	0	00	0	.00
MAJOR 7TH	0	.00	0	.00	0	.00	0	.00	0	.00	0	.00	0	.00	0	.00	0	.00
TRITONE	0	.00	0	.00	0	.00	0	.00	0	.00	0	.00	0	.00	0	.00	0	.00

SHIFTING PROBABILITIES governing one species of Markoff chain music are shown in part here; colored letters key the columns of the table to sections of the music shown on page 118. The probabilities (P) of the intervals are defined by their "weights" (W), which shift according to a simple arithmetical formula. Markoff music has been composed by several similar schemes.

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