FORUM: COMPUTER RESEARCH

THE USE OF COMPUTERS IN MUSICOLOGICAL RESEARCH*

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I PRESUME to speak on the subject of "Computers in Musicological Research" by virtue of two unassailable qualifications: I am not a computer expert, and I am not a musicologist. These, of course, are my qualifications to be presumptuous, not my qualifications to speak. Rather, I should like to think that one of the reasons why I was invited to speak on this subject corresponds to one of the primary reasons that led me to accept: as a confessed Synthesizer expert, and as a convicted composer, I have for so long been exposed and no doubt shall continue to be exposed to, on the one hand, intellectual Luddites, and on the other hand, nonintellectual Luddites, that I have finally been rewarded with the opportunity to address those whose very presence may be assumed to signify that they do not jealously guard their right and that of their fellow humans to do those tasks which can be far more quickly and accurately accomplished by machines. I cannot but believe that all that need be said to such a group of music historians and theorists to demonstrate not only the feasibility but the desirability of computer utilization is to remind them of the nature of the investigations in which they are customarily engaged, and the extent to which such investigations are or should be dependent upon procedures and techniques which have been and are being applied in other fields; those procedures which are normally termed "sub-statistical": indexing, cataloguing, and searching; and those which are genuinely statistical: the formulation of attributive hypotheses in the interests of characterization and attribution, the testing of hypotheses, the sampling of compositions from a compositional population, the determining of correlations between dimensions of a work, between works, and between collections of works, scaling, sequential testing, etc. Unfortunately, the absence of as yet any startling or even definitive re-

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sults in these domains in the field of music history, though certainly the reflection of a temporary practical condition, may be interpreted as temporary refutation. Therefore, as a simple, preliminary instance of computer applications, and one that bridges the pre-computer past with the computer present, I shall take a combinatorial rather than a statistical example—not because it arises in twelve-tone theory, but primarily because it is either familiar already or easily described to those to whom it is not familiar. Surely many of you will recall the first formulations of the notion of an all-interval twelve-tone set in the literature of some thirty years ago, a few years after the first use of such a set in a composition: Berg's *Lyric Suite.* The musical interest of such a set derives from its establishing a structural analogy between pitch classes and interval classes, so that the application of the transformations of the system to the set creates not only a collection of pitch-class permutations, but of interval-class permutations; in such a set, not only do the inverses of the order-number, pitch-class number couples define a function, but so do the inverses of the interval order-number, interval class-number couples. The attempts to formulate necessary and sufficient conditions for the construction of such sets yielded little beyond the obvious necessity that the interval between the first and last element be 6. In the hope that the answer to the purely quantitative inquiry would yield insights into the structure of such a set, and into the system itself, the question usually asked was: how many all-interval sets are there? I doubt if anyone expected the number itself to convey necessarily either surprising or particularly useful information, but such questions seemed a bit more possibly answerable than such existence questions as: are there all-interval sets which contain all ten trichords which are not twelve-tone derivable from one another and yield derived twelve-tone sets in which no two discrete trichords are identical to within transposition? Sadly, both existence and enumerative questions of these kinds served only to demonstrate how little we understood, and still understand, of the structure of the system; and—at that time—asking a human computer to list all orderings of the integers 1–11, inclusive, without repetition, so that no consecutive n of the integers, where $n > 1$, and < 10, sum to 0, mod. 12, seemed not only inhuman, but likely to yield a list susceptible to errors or incompleteness, for all that such a formulation would make the computer's life simpler than that of listing all 12! sets, from which the all-interval ones were to be extracted. This last unrefined approach is probably not much fun for an electronic computer either. In our present computer era, the attempts to formulate the conditions of all-interval structure in still more reduced structural terms have yielded little, but now the approach can be virtually reversed. Stefan Bauer-Mengelberg, Melvin Ferentz, and others at IBM, Hubert Howe and Eric Regener of Princeton, and probably many others, independently have generated the complete list of all-interval sets, in the case of Howe and Regener with all twelve-tone derivable equivalents omitted. Now we can examine a trusted list, and from it attempt to infer principles of construction and relation. So far, we have been able only to formulate still further questions, but these questions themselves presuppose a knowledge we did not possess until the list itself was produced. Now it can be asked: why can no all-interval set begin, for example, with the interval succession 2,6,8? This indicates that as early in the set as the third interval, constraints other than those imposed by nonrepetition of pitch-class and interval-class, and the required tritone between the first and last pitch classes, are involved. Such additional necessary conditions manifestly are associated with the possible partitions of the interval space remaining after these initial intervals, the number of continuations associated with any initial interval, interval pair, or interval succession. But they have not yet been formulated. Now, we possess the highly unexpected result that no all-interval set, for all that one of the most characteristic aspects of an all-interval set is that of its maximal intervallic variety, does contain the 10 trichords described above, although there are some 1,153 sets which do include all 10 such trichords.

Although questions such as these are explicitly twelve-tone, they are questions also associated with the most familiar frequency division of the octave. And they serve to emphasize that the motto of Richard Hamming's volume[1] on numerical methods, "The purpose of computing is insight, not numbers," is not just a scientific homily. Incidentally, there are 1,008 independent all-interval sets.

I trust that whatever apprehensions my introductory example of computer applications and implications may have created were not because I flagrantly disregarded the fact, and the associated terminology, of the three usual representations of the musical event: the graphemic (what Michael Kassler calls the "written musical experience"), the acoustic (Kassler's "produced musical experience"), and the auditory (Kassler's "received musical experience"). The absence of a one-to-one relation between any two of these domains and the lack of sufficient knowledge to translate generally and totally from one to another, particularly from the graphemic to the auditory, make it essential that output information be interpreted only in the domain of the input information. The danger of such confusion appears to be particularly great when the investigation involves the extrapolation from a familiar traditional property, as is the case in my next example, where the content of a major scale is regarded as a combinational (nonordered) selection from the usual twelve pitch

[1] Richard Hamming, *Numerical Methods for Scientists and Engineers,* New York: McGraw Hill, 1962.

classes. It can be shown that the scale is a maximal such collection with regard to unique intervallic multiplicity, and this property automatically defines unique hierarchization with regard to transposition in terms of pitch-class intersection and to within complementary intervals. This is the circle of fifths property. The experiential significance of this property, and its associated entailed characteristics, suggest the need and value of a consideration of various kinds of extensions: to other, particularly prime, equal-tempered divisions of the octave, to specific types of unequal division, and—most immediately—to collections of all sizes and intervallic structures which are transpositionally and inversionally independent, but still within the usual temperament. This latter task has been carried out by computer methods by Howe, and—independently—by Allen Forte.[2] Howe's motivation was primarily compositional, for such complexes are of fundamental interest as combinational units in themselves, as subunits of larger combinational units, as combinational units within permutations (twelve-tone sets or other serial units), or as the combinational representation of a permutational unit or subunit. Forte's motivation appears to have been more immediately analytical, for such collections lie at the foundations of his analytical method for dealing with not primarily triadic, not primarily serial, "contextual" composition, by providing criteria of similarity among pitch-class collections which are spatially, temporally, or transformationally articulated in a composition. And just as such a collection of pitch classes with their associated intervals provides an immediate specification of hierarchization and transposition, so the associated sums of pitch-class pairs specify hierarchization under inversion.

A final computer-resolved question of the same type arose first as a result of Stravinsky's particular use of "rotation" (that is, order-number transpositions) of the elements of a hexachord so that pitch classes of the same order number within each of the six so-arrived at hexachords constituted a "chord."[3] From a number of points of view, it is useful to know if it is possible to construct a hexachord so that each such chord consists of six different pitch classes (except for that chord associated with the first order number, which—necessarily—consists of just one pitch-class). Regener has generated all such hexachords, an unexpectedly large 240 of them, and his program is easily extended to generate hexachords whose so-derived chords possess any specified number of pitch-class duplica-

[2] Allen Forte, "A Theory of Set Complexes for Music," *Journal of Music Theory* (Winter, 1964).

[3] This procedure, with the conditions for pitch repetition and multiplicity, was described in my "Remarks on the Recent Stravinsky," PERSPECTIVES OF NEW MUSIC (Spring-Summer, 1964), p. 53. This technique of rotation itself was first applied by Krenek at least as early as his *Lamentations,* and described by him at least as early as his "New Developments of the Twelve-Tone Technique," *The Music Review,* Vol. IV, No. 2 (May, 1943). Here I am concerned only with those questions that arise in association with Stravinsky's particular use of the procedure.

tions within, between, and among themselves. Here too, new and difficult questions can be formulated on the basis of the information derived from the computation: why are the only all-combinatorial hexachords which yield chords without pitch-class duplication trichordally-derived hexachords, and—thus—degenerate under twelve-tone transformations?

Such interrogations of the computer as the three just mentioned are founded on the supplying of an algorithm, a specification characterizing a provably effective process, and result in the securing of specific results of the application of the algorithm to a particular collection, either enumerated or enumerable through a specified rule of construction. Such a process involves the supplying of little data as such compared with the quantity of data occurring in the output. The process in which the output data is a subset of the data placed in the computer, a selection from that material, characterizes the field of information retrieval. Since this is a domain which may include many of the resources of particular relevance to musicologists, I shall describe it by quoting the authoritative words of Bar-Hillel: "Assuming that there exists somewhere a body of recorded knowledge—in technical terms, a collection of documents—and assuming that someone has a certain problem for the solution of which this collection might contain pertinent material, how shall he decide whether there are in fact documents in this collection that contain such pertinent material, and, if so, how shall this material be brought to his attention?"[4] If this question is obviously relevant to musical research when the body of recorded knowledge involved is the literature on music, and by a conceptually simple if not technologically equally simple extension, when it is assumed to be the literature of music, then the already vast research on information retrieval is probably the first object to which the musical scholar should apply its techniques. The specific procedures and, even, the general value of computer application in these areas is very much a matter of controversy among experts, and the issues carry one into linguistic analysis, content analysis, item distance (in this respect, for example, mathematical notions from lattice theory and topology have been introduced into indexing theory), and other highly specialized disciplines. Manifestly, the nonspecialist cannot presume to choose among the techniques or even among the specialists at this unsettled stage of the activity, but some of the issues involved should be presented. Basically, there is the general question of indexing documents so that those documents germane to a stated topic can be located under the simplest possible interrogation, where simplicity is subject to definition in practical terms, and where the decision of placing the borders of relevance between the points that would yield too many false drops and unjustified blank

[4] Yehoshua Bar-Hillel, in *Digital Information Processors,* ed. W. Hoffman, New York: John Wiley, 1962.

sorts, this is, between demands of too little relevance and those of too great relevance, is a critical decision. Even merely relatively satisfactory solutions appear to involve translation, exact and apparent synonymousness, frequency criteria, transformational analysis, semiformalized languages, etc. If the data to be queried are stored representations of notated music rather than notated language, we are at least in as difficult a position, and apparently in an even more difficult position when it comes to the labor and cost of getting the data into storage without character recognition devices, with which, from a standpoint of human operator involvement, the input form of the musical information is the printed or handwritten score, or parts. In the initial stages, at least, it is likely that interrogations of a musical nature will have to depend less on indexing, for—in a sense—the queries will have to be an attempt to derive what could be regarded as criteria for indexing. In such a case, there can be little doubt as to the enormous value of the computer as an information "amplifier." In the simplest possible terms, the specification of a single musical event in terms of, say, six coordinates (pitch class, registral class, duration, dynamic, timbre, and metrical placement) means that it can be compared with another, say, pair of events in 216 ways, from a standpoint of mere identity and nonidentity with respect to each of these dimensions. In other words, for each half-dozen simple input specifications, there is an exponential increase in correlation information; and under realistically practical conditions, the degree of amplification is even greater, for there will be qualitative and quantitative scales in each of the dimensions represented by a coordinate. And such correlations, in their extensions as concept-defining, surely must be the elements on which style analysis is to be founded. In this area of computer applications, I should like to mention a project which is being undertaken at Princeton University under the direction of Arthur Mendel and Lewis Lockwood. By the time this article appears, all of the complete masses attributed to Josquin, as well as some mass sections and the model compositions for some of these works will have been key-punched, and there will then begin a series of stylistic interrogations of this material; questions of intervallic succession and simultaneity, correlations between text and music, decisions as to matters of "ficta," etc. should be forthcoming very soon. (Although one of the subjects specifically excluded from this discussion is that of the structure, availability, and appropriateness of the various "languages" for transforming the language of common musical notation through the required stages into that of the machine language of a particular computer, it should be said that the Josquin project has employed MIR, developed by Kassler, and that there exist already in addition to MIR, LMT and IML among others, in some cases for different tasks, and representing different stages of the transformation;

all look forward to being superseded by character recognition equipment.)

With the notion of style, we arrive at a point of common interest and —probably—procedures between musical and literary research, in the latter case some of the research has been undertaken and accomplished already. Perhaps the most celebrated and certainly the most sophisticated instance is that contained in Mosteller's and Wallace's attempt to determine the authorship of the disputed Federalist Papers. Without becoming involved in the statistical technicalities, there are the important points that the problem was formulated in such a way that its solution could have been reached reasonably only by computer utilization, and that the style characterization involved the use of style attributes not as simple attributive predicates, but as binary and ternary relational predicates; this brings into focus the methodological danger—at least—of attempting to speak of style attributatively. Surely, under all customary conditions, the term "style" is used as supervenient, not as simply primitive. Therefore, if one asks a computer to characterize the style of a work or a collection of works by determining the range of values of certain dimensions, this condition is satisfied at one extreme by the sufficiency of any dimensional value, and—at the other extreme—cannot be satisfied at all in practical finite terms, since every condition will have to be regarded as necessary; and, therefore, there are an infinite number of values required for the specification of necessity, or to discriminate it from a nonidentical work, at least in the graphemic and acoustic domains. It would seem reasonable, and the Mosteller-Wallace paper adds support to this view, to decide that style should be sequentially characterized and determined by paired comparisons of similarity with reference to a third, attributatively defined instance or collection of instances, so that membership to the attributative class of the instance, or instances, can then be granted qualitatively to one or the other of the pair, assuming them to be nonequivalent.

The compounding of simple correlations into fruitful concepts probably gives rise to many of the problems associated with indexing, for this process easily can lead to that of formulating rational reconstructions, of attempting to provide explanatory notions of specified scope, and thus into the area of computer simulation, but simulation not of structure but of function. Simulation of structure, which smacks dangerously of the attempted mechanization of the intentional error, would carry the discussion toward at least one area which is to be excluded here, that of "computer composition," particularly the case in which the process of composition is "simulated," but simulation of function, in which composition is, in an important sense, inverse analysis, therefore involves the structure of systems, and the testing of the systematic rules for adequacy. The first work of this kind which attracted general attention and had general influence was that of Lejaren Hiller and his associates at the University of Illinois, where the first system tested for accuracy and adequacy was that associated, more or less, with the contrapuntal rules of Fux.

Surely, now we can speak of randomness in a responsible way, in terms of inter-symbol dependence; and I emphasize the word "symbol," for it is particularly in this kind of investigation that the most crucial mistakes can be made by confusing the domains of the input premises and the output conclusions. A finite numerical sequence, derived—in testing constraints—from a random number table, must establish its rules of correlation with notational rather than auditory entities, simply because the bases for such correlation are not yet completely enough known. The use of computers to test systems, particularly in the sense of demonstrating the consequences of their constraints, is of fundamental importance in clarifying the notion of a system and of not inconsiderable, if peripheral, importance in defining areas of ignorance, both at the points where the constraints must be formulated, and at the point revealed by the output discrepancies between the result and the population which it was intended to represent. As an immediate example of such testable ignorance, consider the problem of formulating constraints for rhythmic progression in, say, just the string quartets of Mozart. And, if one wishes to reach the analytical point where all of the dimensions of musical events are considered in their interaction, how many paths must there be through a realistically constrained musical work, when it has been estimated that there are probably some 10^{120} paths through a game of chess?

The most ambitious analytical effort of which I am aware is the formulation, not yet computer-tested, by Kassler of the transformations of the analytical theory of Heinrich Schenker. I note that this elaborate instance of hypothesis testing employs primitive-recursive functions only to emphasize that the use of a known formal system as the model of a musically interpreted theory or system makes possible the interpretation of theorems of the formal system to yield interpreted generalities that would otherwise very likely go undiscovered. Contemporary musical composition already has employed many of the fruits of this procedure, and—for our discussion—there is the further consideration that the theorem-proving capacity of a computer may well be used, therefore, to provide explanatory and compositional results in the musically-interpreted domain. I shall mention only one such totally new musical result derived, by obvious rules of correlation, from a familiar "formal" theorem: there is a common system of pitch-class representatives between any two partitions of the same order applied to the same pitch-class collection. An examination of this common system in different cases suggests that the explanatory consequences of this statement are very great, and surely the notion is suggestive compositionally if only that it provides a means of weighting a pitch collection as a connective between two otherwise highly dissimilar collections.

The fact that statements of relatedness within a composition are usually totally or largely without reference to temporal position when the events in question are not immediately adjacent and extremely simple is another indication of the need for the resources of the computer, for the notion that a theory of a body of music or of a single composition could consist satisfactorily of statements founded on time independence contravenes our whole conception of music as proceeding in time. Stated in rather more chic terms, we apparently are prepared to speak of the transition probabilities from, say, note to note, but not from note configuration to configuration, and surely not from total configuration to configuration. In other words, our formulation of a list of allowable transformations provides little or no information about the relation of the nature of the transformation to its temporal position. Obviously, the reason for this is the sheer quantity of material that would have to be processed for such a formulation, but already precedents are being established: it is not difficult to imagine how one could apply the techniques of the Gottshalt visual tests to processes of variation, pitch embedding rather than the embedding of visual configurations.

The direct computer production of sound is another of the subjects excluded from this discussion, and, fortunately it already has its own valuable literature.[5] The noncompositional uses of this method, however, are not alluded to in this literature and bear listing. The Josquin project, referred to above, has been using the Music IV program to provide aural proofreading of the key-punching of the scores. The actual sonic materials for psychoacoustical research, as well as the lists of such stimuli, could and probably should be prepared by computer. The investigation of the dimensions of so-called "timbre," not in order to "duplicate" timbres, but to test the results of duplicating their dimensionality, this involving analysis by synthesis, is most easily undertaken by the interrelation of the computer as instrument of sound analysis and production. Entry into the most refractory of areas, that of auditory perception, is afforded by the computer by processing and deriving significantly new conclusions from the responses elicited and recorded by the computer. For instance, the dimensions of contextually perceived timbre should be derivable by the method of multidimensional scaling;[6] this

[5] A representative list includes: M. V. Matthews, "An Acoustic Compiler for Music and Psychological Stimuli," *The Bell System Technical Journal* (May, 1961); James Tenney, "Sound-Generation by Means of a Digital Computer," *The Journal of Music Theory* (Spring, 1963); James Randall's article in this journal.

[6] Warren S. Torgerson, *Theory and Methods of Scaling,* New York: John Wiley, 1958, Ch. 11.

method requires only that the subjects be able to arrange three stimuli according to the relation of "more similar than," that is, A is more similar to B than to C, for example. (This method, unlike those more familiar, does not require any prior assumption of dimensionality.) If this question appears unanswerable for a given dimension such as tone color, then one can conclude that the structuring of tone color is not perceptually possible, since similitude relationships in this domain are concluded to be without uniformity and determinacy. If the question is answerable, then the dimensionality of the domain is determined by a method which is very simple in terms of a computer's capabilities: the inter-event ordinal distances are squared and placed in a bordered matrix, the rank of which is, then, two more than the dimensionality of the events in question. These relative technicalities are mentioned only to provide an instance of what would be a discouragingly formidable computational task if computer routines were not readily available. Such availability not only makes a solution accessible to those who can only run the program without possessing the mathematical techniques for formulating or arriving at such a solution, but provides reliable results to those who do not even comprehend the mathematical procedures involved. This is a fact of enormous pedagogical consequences, since easily and quickly acquirable computer knowledge places one in the position to employ and apply advanced techniques and results derived from a broad inter-disciplinary range without obliging one to undertake the manifestly hopeless task of acquiring more than a passive knowledge of the material of this range.

The first decade of general computer use has but just ended; little of that decade of computer time has been applied to musical research or production, so there is as yet relatively little to show and only slightly more to tell, but the second decade can be only radically different; indeed, it already is.