Notes on Electroacoustic Music

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1 From Experimental to Omnipresent

It is ironic that electroacoustic music, which began in outspoken opposition to the music of the past, and which met with so much opposition—or, where opposition seemed too honorable, then neglect—from established musical circles during the 1950's, became so thoroughly co-opted by most of the forces of music against which the revolution had thought to do battle.

Today's electroacoustic music is descended from two venerable sources, the *musique concrète* which began in 1948 in the Club d'Essai in Paris under the direction of Pierre Schaeffer, and *elektronische Musik*, which began in the studios of the then Nordwestdeutscher Rundfunk in Cologne under the direction of Herbert Eimert.[1] The aesthetic intentions of the two studios were, as it seemed at the time, diametrically opposed. *Musique concrète* used as its basic material recorded sounds, music, speech, sounds from the everyday world, noise. These sounds were transformed by operations using the equipment found in a radio studio, transposed, reversed, filtered, fragmented, recombined, mixed together. It was an important philosophical tenet of the group around Schaeffer that the ear is best adapted to the perception of acoustically complex natural sounds and that this complexity would remain present in the resulting music, investing it with a liveliness that "artificial" sound could never have. Herbert Eimert, on the other hand, proposed a music whose basic sound material would be made wholly by electroacoustic means, which in the early 1950's meant building complex sounds from simple components like a sine wave or an impulse train, before manipulating these sounds by essentially the same techniques as those proposed by Schaeffer. Today, in a more pragmatic age, when electroacoustic composition generally makes indiscriminate use of both ways of working, the differences between these philosophies may seem of little importance; the article "*Musique concrète*" in the *Encyclopédie de la Musique* (1958) by Pierre Boulez, however, gives evidence of the virulence of the confrontation of 30 years ago.

Despite their profound differences, the two schools of electroacoustic music shared the conviction that their music was a radical departure from the music of the past, and while neither school quite dared to claim to be the only true music of the future, messianic fervor accompanied the work of both throughout the 1950's. As after 1945 one was rebuilding the cities—and of course the whole social fabric—of Europe, so one would also rebuild Music (this idea was not limited to electroacoustic music, obviously; the conviction of establishing new, universally valid laws and techniques announces itself clarion-like from the considerable body of polemic/pedagogic literature on serial music). This vision of a New Atlantis[2], where new, yet to be discovered musical laws would obtain, was a motivating force in all the electroacoustic music of the 1950's. (Even in more jaded times it must be the rare composer of electroacoustic music who can claim complete immunity from the idea of working on a frontier.) Concomitant with this abrupt rejection of the aesthetic framework of the music of the past, and ultimately much more important, was the elaboration of a theory of the importance of experimentation in electroacoustic music. To be fair, the idea of experimental music was more clearly articulated in Paris than in Cologne, where experimental techniques were certainly used and where the most important works coming from the studio, like *Kontakte* (1958) by Stockhausen, can only be described as experimental, but where the experimentation masqueraded as operations deriving from complex serial manipulations, as though thus to become intellectually and aesthetically more acceptable.[3] Schaeffer, however, had from the beginning spoken of "*musique expérimentale*". It is worth noting that in the introduction to the issue of the *Revue Musicale* (1957) bearing the title "Vers une musique expérimentale"[4] Schaeffer lists three postulates and five rules for concrete music; four of the five rules require: a new solfège, the creation of *objets sonores* and of *objets musicaux* (new instruments) and the working out of études; he does not speak of definitive works. Much of Schaeffer's own production is entitled *Etude sur...*, and the open, non-definitive quality of his music is immediately apparent and is one of its most winning characteristics.

"Experimental" in a musical context is not easy to define. It characterizes a radical position towards all levels of musical structure: phonological, grammatical, syntactic and the level of discourse, to use linguistic metaphors. The sound material of experimental music is new, not heard before; the interrelationships, connections, juxtapositions and combinations of "objects" are constantly surprising; the attitude of a piece to its public, to speak anthropomorphically, differs from that of all other pieces: the listener is expected to find his way anew to each piece. The experimental quality of early electroacoustic music was certainly supported by the technology. There were no special-purpose electroacoustic instruments, only tape recorders, tone generators, filters and the like. Each phrase of each composition required a different technical solution, and the solution could only be found by experimentation. On the one hand, the experimental postulate for electroacoustic music might be considered making the best of a difficult technical situation. On the other, many composers found their appetite for the new and unexpected growing until it became a kind of obsession: music which did not have a high degree of differentiation in sound structure and which did not offer constant kaleidoscopic change was felt to be shoddy, vaguely dishonest, certainly non-experimental.[5] The fact that a composer had to do everything by hand in an electroacoustic piece contributed greatly to the formal density and complexity of the pieces from this time, and, one might add, in many cases to their interest for listeners today. Certainly nothing was free in the 1950's, except maybe the continuous sine wave, and the necessity of thinking carefully about the shape and content of a piece before beginning work led to many quite remarkable works.

But this same force that so strongly supported experimental music—put bluntly, the difficulty of doing anything at all—also ultimately led away from experimental music. As the interest in electroacoustic techniques grew among musicians, specialized instruments began to be constructed (for example by Robert Moog and Donald Buchla in the United States in the early 1960's and somewhat later by Peter Zinoviev in Great Britain) which combined into one device some of the sound sources (generally tone-generators with fixed wave shapes) and transformation devices (filters, envelope generators, ring modulators) which had been used as separate elements in large studios.[6] In fact, these new instruments often offered greater flexibility than did the large studios, for their individual components could be interconnected in virtually any combination. These synthesizers were first produced on special order for musicians working experimentally, often in what was already then a no-man's land between "classical" and "popular" music. The success story of the Moog synthesizers is very instructive about the development of synthesizers and the forces at work in this marketplace. During several years Robert Moog constructed innovative and original synthesizer modules for a small but devoted clientele. If this was an exciting time because of constant invention and because of the intensive collaboration with musicians interested in experimental aspects of music, it was also a financially very difficult time. Moog and his small company were surprised and gratified when Wendy Carlos' record *Switched-On Bach* (1968), which was made using Moog components, was a great success. Orders for Moog instruments poured in, the name Moog became practically synonymous with "synthesizer", and the company prospered, so much so that it attracted the attention of and was eventually taken over by a large diversified company. The parent company expected continued growth, which meant opening new markets among musicians who had not yet had the courage to use synthesizers. Soon there was pressure on the designers to simplify the synthesizers, to reduce interconnection possibilities to a set of standard solutions, to abandon the modularity which had been such an important concept both for the designers and for the clients. For a while the market did increase, but the instruments lost all attractiveness to anyone interested in electroacoustic music in an experimental sense. Robert Moog eventually sold his share in his company and is at present looking for an interesting musical project to which to devote his time and energy.[7] Of the important early synthesizer designers, only Don Buchla continues to produce a very small number of instruments on special order. Virtually all the rest of the market is covered by the large manufacturers of electronic devices.

Robert Moog's story is paradigmatic for the commercial forces seeking to co-opt the fruits of experimental music.[8] Of course the experimental aspect of electroacoustic music—a searching ear, a sensitivity to and reticence about any kind of unreflected repetition, an almost aggressive avoidance of anything smacking of cliché—still exists and marks the music of certain composers of all generations. The irony is that in the early days one dreamt of a technology which would permit a far more radically experimental composition; today that technology exists, and it makes experimental music more difficult than ever.

2 Live or Composed?

One of the questions about which allegiances are almost always clear is the issue of live electroacoustic music versus tape music. The antagonism, or at least the opposition, is older than one might think. The earliest electroacoustic instruments—the Theremin, the Ondes Martenot or the Trautonium[9]—were concert instruments to be played like a piano or an organ. But it was the introduction of inexpensive magnetic tape in the European radios after the Second World War (magnetic tape had been used since 1935) which marked the beginning of electroacoustic music as we know it today. The music of the Paris and the Cologne studios was at first exclusively tape music (the Paris studio used phonograph records until 1951). Schaeffer's *musique concrète* depended on tape manipulation techniques, and the *elektronische Musik* of Cologne required large, not easily mobile equipment for its sound production and like *musique concrète* usually required several passages of the same material through various pieces of apparatus before it was mixed into definitive form. But if the studio equipment couldn't easily be brought into the concert hall, the tape recorder could. The use of tape music as an accompaniment to instrumental music is virtually as old as electroacoustic music itself; Bruno Maderna's *Musica su due dimensioni* for flute and tape was written in 1951 (later versions in 1957 and 1963). In some respects the technology of tape music has changed little since its beginnings in the 1950's. However, one very important technological innovation for tape music was the development of programs for sound synthesis and processing on digital computers, beginning with the work of Max Mathews at Bell Laboratories in the late 1950's. Mathews's programs have since been extended and adapted to many different computer environments; they form the basis for most of the musical work done in computer music studios throughout the world. The development of small digital synthesizers and processors used in live electroacoustic music has depended upon research done using the technology developed by Mathews.

Unlike tape music, live electroacoustic music has benefited from almost continuous technological development. To begin with, live electroacoustic music was dependent on the advances made in the technology of commercial high fidelity and on the transistorization of electronic devices. An early live electronic piece is Cage's *Cartridge Music* (1960), in which phonograph cartridges are used as transducers for all sorts of sounds. Takehisa Kosugi wrote *Micro I*, a piece for microphone alone, in 1961. Stockhausen took a few of the simplest instruments from the studio into the concert hall in 1964 for the pieces *Mikrophonie I* and *Mixtur*; several other compositions for live electronics and instruments followed. Much of the live music of the 1960's was made with specially built equipment or made use of conventional objects in unusual ways (examples are David Tudor's pieces *Fluorescent Sound* (1964), in which resonances of fluorescent tubes were amplified and filtered and *Rain Forest*, which reproduced electronic sounds not through loudspeakers but using various objects of metal, plastic and wood). The 1970's saw the astonishingly rapid development of commercial synthesizers and of an immense market for them, primarily in popular music. These instruments were usually equipped with keyboards and could be played like conventional instruments, which greatly increased their attractiveness. The most important technical advance was the use of voltage control in many of these synthesizers, which greatly increased their precision and made them programmable. During this time, cheap micro-computers appeared (the Apple II in 1976, the Commodore Pet in 1977) and were often used to provide the control voltages for synthesizers, thus allowing the development of complex scores for these instruments. In 1983 several manufacturers of electronic musical instruments agreed on a protocol for the transmission of data in digital form between instruments (Musical Instrument Digital Interface, MIDI). The subsequent acceptance of the MIDI protocol by virtually all builders of electronic instruments, itself absolutely unprecedented in commercial music, has probably been the single most important development in electroacoustic music since its beginnings.

At present, live electroacoustic music seems in much greater favor than tape music. It is not hard to understand why. Many musicians are instrumentalists for whom the physical experience of making music is at least as important as the acoustic result. The realization of tape music takes place at a greater remove from the material than is comfortable for many composers (the realization of music synthesized and processed by computer, where there is no physical manipulation of any kind, at a yet greater degree of removal). Audiences often find it easier to identify with music whose genesis they can watch, and there is no denying the awkwardness of a concert where an expectant audience is greeted only by several more or less elegant loud speakers on a stage. Nor do we live any longer in a time in which the newness, strangeness or radicalism of a piece are felt to have direct positive bearing on its aesthetic import. Tape music is often felt to be impersonal, inflexible, unnatural, live electroacoustic music direct, supple, a humanized application of technology to music.

It is true that tape music, whatever the technological means used for its production, does not feel like instrumental music. Part of the joy of listening to music for an experienced listener is to follow the acoustic trajectory of a sound or a phrase back to its physical origin. The reflex of asking not only "what do I hear?", but also "what is making that sound how?", is older than music (older than almost everything: it is one of the ways of answering the question: "Can I eat it, or will it eat me?"). Not only can the movements producing an instrumental sound usually be inferred from the sound itself, physical effort and mechanical resistance gauged, the emotional thrust of even unfamiliar music accurately sensed, but an experienced listener recognizes in all this inferred physical information patterns and regularity which are given by the nature of physical matter itself and which thereby take on a legitimacy the acoustical level of the music alone might not seem to merit. In live electroacoustic music, even where there is not a clear relationship between the movements of the players and the sounds one hears, the "human" influence announces itself through temporal relationships, inflections of pitch, the way one improvisatory phrase is related to the next, etc. Tape music generally, unless it takes pains to imitate instrumental situations, communicates little or none of this physical information, and where the ear seems to be able to infer something about the mode of production of sounds or phrases, this pseudo-physical information is usually confused and incoherent, because the constraints of the physical world played no role in the sounds' origin. But while tape music sounds and feels different than instrumental music, this fact can hardly serve as an argument for the superiority of live electroacoustic music. Forty years ago, this very difference was one of the main arguments of an avant-garde proposing electroacoustic music as the music of the future. But if live music seems to offer a suppleness which tape music cannot match, tape music consistently shows a degree of musical complexity which live electroacoustic music seldom attains. It is not immediately clear why this should be so; after all, it only takes one person to play a Beethoven sonata or a Bach fugue, about whose musical complexity there can be no question. But in music where the burden of the music statement is in the movement of harmonies within a landscape whose geography is well understood (F-sharp major is always at the same distance from C major), of melodies in relation to these harmonies and of the passage not only of chronological time but also of metrically articulated time, the role of the performer is largely one of putting temporal order to the score. The high degree of individuality which the interpretation of a piece can have depends acoustically primarily upon differences in precisely when (with what anticipation or delay in relation to the meter) a note or a chord is played; it depends psychologically upon the patterns the listener discovers in the performer's temporal distortion of the score. Much of the expressive energy of an interpretation may well depend upon parallels the listener draws between these patterns and similar patterns of physical movement in the everyday world (for example the parallel between the slowing down at the end of a phrase and the slowing down from walking or running to standing still, or between the pause before playing a surprising and distant harmony and the pause to collect one's strength before moving a heavy object). In most electroacoustic music, however, the burden of the musical statement is not to be found in the distortion of more or less regular temporal patterns, nor do harmonic relationships play the structural role they do in the music of the 18th and 19th centuries. There is instead, in much of electroacoustic music, a shifting of the compositional attention to the sound itself.

A slogan in the early days of electroacoustic music exhorted: "Not to compose with sounds, but to compose the sounds themselves." Composing the sounds turned out to be a fairly difficult procedure, requiring extremely precise control over the frequency and amplitude of individual components of a sound; in fact, only digital sound synthesis and processing really allow this kind of control, but traditional studio techniques combined with specialized equipment (samplers, harmonizers, reverberators and room simulators—themselves all devices based on digital technology) permit composers some degree of freedom in defining and modifying the inner structure of sound as well. In general, however, this precise control over sound does not lend itself very well to use in live situations, for two reasons. In the first place, the computations required for complex synthesis and processing, despite the advances made in digital technology, remain time-consuming. Contemporary commercial digital synthesizers achieve high-quality synthesis in real time by limiting drastically both the number of parameters which are allowed to act upon the synthesis and the number of values a given parameter can take in the synthesis. The increasing use of special processors together with microcomputers has brought remarkable increases in synthesis power. Nevertheless, it seems fair to assume that general digital synthesis and processing in real time will remain extremely difficult in the reasonable future.[10] Secondly, complex synthesis requires a large number of parameters, most of which can be assumed to be changing simultaneously. The number of things a performer can control at one time is not really limited by the number of fingers he has, say, but in the general case by the number of polyphonic voices he can follow at one time, which will be somewhere between three and five. This is why live electroacoustic music so often deals with "prepackaged" sounds, relegating the real time control to traditional and "simple" aspects like start time, amplitude and some direct influencing of timbre.

Perhaps however the goal should not be to achieve the richness of tape music with one complex instrument in real time. Perhaps one should rather dream of orchestras of complex instruments, each one played by an experienced performer who has practiced his instrument for years, after the model of the classical orchestra or the string quartet. But this of course is a musician's dream and there is a serious stumbling block: the propensity of technology to keep moving, not to be satisfied with one result, always to wish for improvement. In the years it would take a performer to learn to play an instrument well, the instrument itself would be "improved" many times over, leaving the conscientious performer isolated at the very least in terms of maintenance of his instrument, if not more directly in terms of possibilities of connection, interfacing, etc. As long as the manufacture of commercial electroacoustic instruments continues to be big business, it is difficult to imagine one instrument remaining stable long enough (ten to fifteen years) to allow it to accumulate a reservoir of technical excellence and a sufficiently large body of literature to assure further transmission of this excellence. (And when the manufacture of commercial instruments is no longer big business, it is hard to imagine how individual instruments could ever achieve the broad user base necessary for the emergence of a literature.)

There is a natural tension between tape music and interactive, live electroacoustic music. What the one excels in, the other does rather poorly. It would seem that this antagonism lies deep in the nature of the two modes of making music, or at least in the technological prerequisites for their realizations. There may always be musical and expressive tasks for which tape music will be more adequate; there will certainly always be interest in the directness of instrumental music, even at the cost of compositional complexity. The differences between the two ways of working and playing music should rather be rejoiced in and cultivated, each offering subtleties of expression which the other cannot.

3 The Resistance of Natural Sounds to Complex Manipulation

Electroacoustic music would seem to be the great equalizer: all sounds can be dealt with in the same way, all are equally pliable in transformation, all can serve equally well as compositional material, no longer is there any distinction between "musical" and "non-musical" sounds. In fact, this is not true. Natural sounds have proven remarkably intractable and resistant to any but the crudest manipulation. The following discussion will necessarily be a bit technical, for it is in the technical detail (and of course in the sound itself) that this intractability can be best understood. At the same time, this toughness of the sonorous material is a kind of wonder, telling us something about the nature of the world and of our understanding of it.

For some years during the 1980's the popular market seemed to agree that sampling machines would provide the solution to the aridness of synthesized electronic sound. Samplers are instruments which record digitally sounds from the "real world" and manipulate them in real time. That samplers should provide an antidote to the preceding decade or so of synthesizer sound is a rehashing, no longer on a local or national level this time, of the confrontation between *musique concrète* and *elektronische Musik* in the early 1950's: sampled sound would contain a natural liveliness, which would persist through any transformations one might perform. Samplers have brought the world musical treasures like dogs barking in chorus or cows lowing a catchy melody.

The first and intuitively simplest transformation, and that which all samplers offer, is transposition. Most samplers have keyboards, and a recorded sound can be projected onto the keyboard and transposed by any ratio of the chromatic scale within the range of transposition permitted by the particular sampler. The transposition in most samplers operates like transposing with a tape recorder: the recorded sound is played back at a different speed than that at which it was recorded: more quickly for higher frequencies, more slowly for lower frequencies.[11] The resulting sounds are correspondingly lengthened or shortened. But there are other problems. The first concerns the process of transposition itself. Low sounds on a piano, for example, have a lower fundamental frequency than do higher tones, but may have partials (overtones) just as high. For technical reasons, digitized sounds contain no energy above a specific frequency. As a digitized sound is transposed down, this point above which there is no energy moves down as well. The result is as if a filter were moving with the transposed sound, making it less brilliant as it gets lower. Transposition upwards, on the other hand, suffers from loss of energy as the sound moves up, although it is easy to compensate for this loss so that the amplitude remains constant over the entire transposition range, at the risk however of distorting the timbre of the sound. Another problem stems from the fact that most natural sounds contain information about the physical objects producing them: the friction of bow hairs on the string of a violin, for example, the resistance of the string to being set into motion, or the way the wood of the violin favors some frequencies and dampens others. The ear is very good at making guesses about the nature of an object producing a certain sound, and many sounds offend the ear when transposed in an extreme way, not because of their acoustical quality, but because of the distorted physical information they transmit. A good example is the "Mickey Mouse effect" one gets by transposing speech or singing an octave higher using a tape recorder. Certain frequencies of the voice are reinforced by resonance in the vocal tract. Which frequencies are reinforced depends directly on the size of the cavities of the vocal tract. When speech or singing are transposed up, not only do the frequencies of the resonances change, but also the perceived interval between the resonances; one "hears" a much smaller individual speaking because of one's analysis of the physical information conveyed by the sound. Here the sound itself is clearly resisting facile manipulation.

Techniques do exist to manipulate real sound in subtle ways, but they all require first translation of the sound into the frequency domain, manipulation of the frequency information and then translation back into the time domain, operations which must be done digitally and which are relatively costly in computation time.[12] The difficulty of these manipulations shows dramatically the intransigence of natural sounds, which carry with them the traces of their origins. To use pre-recorded natural or instrumental sounds in an electroacoustic context will in general required complex digital operations and can probably be accomplished best not in real time.

4 The Non-Analyzability of Electroacoustic Music and the Consequences of an Oral Tradition

Electroacoustic music, unlike instrumental music, has nothing even approximately approaching an accepted notation. Composers have taken several approaches. One is to indicate how the composition was realized, a sort of work report. This is the solution taken in one part of the score of *Kontakte* by Stockhausen, where the individual operations leading to the finished tape are described in considerable detail. Another approach is to draw a score representing graphically and symbolically electronic events in the "frequency domain". Live electroacoustic music, on the other hand, often uses a tabulature notation, showing what must be played when. Of these three possibilities, only the first serves as an objective notation in any real sense.

Musical notation traditionally fulfils different functions. The first, of course, is to tell players what to play and when to play it. The second function is one of conservation: the music of the past has come down to us exclusively in notated form. The third function lies somewhere between the immediacy of performance and the near-eternity of conservation: that of reflection and analysis. Much electroacoustic music does not require notation in the first sense; music without performers does not need a performance score. The second function has been superseded by the recording, in whatever form, of the music itself.[13] However, the replacement of notated music by a unique form of a piece is a step of enormous consequence: the shift from a literate to an oral culture. The third function, that of analysis, has virtually ceased to exist in electroacoustic music.

That electroacoustic music is not analyzable in a traditional sense makes it like a vast organism of boundless energy and liveliness but without a head. Not that individual practitioners are headless, or that they work without method or do not structure their music as carefully as instrumental composers; the non-analyzability means that every musical technical discovery remains anecdotal, ephemeral, or just plain secret. The non-analyzability also means that no discussion of handicraft—*Handwerk*—can take place between composer colleagues, or between experienced and less experienced composers, except in the studio directly with the musical materials and the equipment. (Aesthetic discussions have traditionally not been limited to those who can read music, or even to those who know anything about music. It seems reasonable to expect that in this regard electroacoustic music will remain true to tradition.) There is, however, another discussion which often does not take place in composing music without notation: that of the composer with the abstraction of his material. In the composition of instrumental music, notation is not only the tool for communicating the composer's thoughts to the performers; it is also the language in which many ideas manifest and express themselves during the compositional process. The notation offers a sufficiently abstract representation of musical events that the composer can use it to clarify and focus ideas which presented themselves either as sensuous experience (a chord, a melody, a kind of instrumental sonority) or as idea divorced from a specific material realization (rhythmic motif, set of proportions, etc.). This passage from sensuous experience to more abstractly formulated material is of great importance for composition and is only possible to a limited degree in electroacoustic music. In compensation, one works much closer to the sonorous material in electroacoustic music than in instrumental music; composition is often an intense sensuous experience, sometimes almost intoxicating. And much electroacoustic music reflects this experience by great sensual suggestivity, often entering into one's consciousness by dark and mysterious ways, very different from most instrumental music.

The non-analyzability of electroacoustic music, which is due to the lack of an accepted notation, is responsible for the direct sensuous appeal of much of this music. The price for this direct appeal is the impossibility of a common dialogue about technique. Ironically enough, to sound a theme often raised before, commercial music is more than willing to fill this vacuum. Commercial electroacoustic instruments are physical expression and embodiment of theoretical and musical technical ideas often of great ingenuity and interest. We composers most often engage in discussion with each other about machines, not only to disguise our shyness about talking about aesthetic matters, but because we have no technical analytical language, or more precisely because the machines have become our technical language.

There is remedy, or at least partial remedy, for this illiteracy, this aphasia, this demeaning dependence on and devotion to machines. The remedy is, as so often, knowledge. The more a composer knows of the mechanisms and techniques necessary for the production of electroacoustic music, the better he understands the operation of his instruments and especially their limitations, then the more his ideas will begin to express themselves in terms more directly related to the processes he employs. The more a composer learns to relate sensuous experience to acoustical and technical processes, the greater the abstraction with which his ideas will express themselves. The greater this abstraction, the greater his independence from the machines he uses, and the greater the chance of meaningful dialogue with his colleagues. Only thus can electroacoustic music hope to establish any meaningful tradition, hope to develop a pedagogy worthy of the name, hope to move from a largely unreflected culture to one mature and responsible.

5 A Good Year

The year 1958 was a good one for electroacoustic music (although one might argue that all years have been good for electroacoustic music). Here are some of the pieces composed and realized during the year:[14]

Almuro, A., *Erostrauss*, Paris
Almuro, A., *Hermaphrodite*, Paris
Almuro, A., *L'éternel enfantin*, Paris
Almuro, A., *La chambre d'à côté*, Paris
Almuro, A., *Le deuxième monde*, Paris
Almuro, A., *Les Gus*, Paris
Almuro, A., *The Ox and the Ass*, London
Artuys, P. and I. Malec, *Avant le Petit-déjeuner*, Paris
Artuys, P. and I. Malec, *Le Bateau*, Paris
Artuys, P., *India*, Paris
Artuys, P., *Jardin de Corail*, Paris
Badings, H., *De Horschelp*, Hilversum
Badings, H., *Dialogues pour l'homme et la machine*, Paris.
Badings, H., *Tune*, Hilversum
Baronnet, J., *La voix*, Paris
Barron, Louis and Bebe, *Ballet Score*, New York
Barron, Louis and Bebe, *Bridges*, New York
Barron, Louis and Bebe, *Firstborn*, New York
Berger, R. und Ilya Zeljenka, *Étude 1*, Bratislava
Berger, R. und Ilya Zeljenka, *Étude 2*, Bratislava
Berger, R. und Ilya Zeljenka, *Étude 3*, Bratislava
Berio, L., *Musica di Scena no. 9*, Milan
Berio, L., *Thema (Omaggio a Joyce)*, Milan
Berk, E. *Slide Tape no. 1*, London
Berk, E., *Somnambulist*, London
Boucourechliev, A., *Texte I*, Paris

Boulez, P. *Poésie pour Pouvoir*, Baden-Baden
Bruyndonckx, J., Rails, *Herentals* (Belgium)
Brün, H., *Anepigraphie*, Cologne
Brün, H., *König Lear*, Cologne
C. Cardew, *First Exercise*, Cologne
C. Cardew, *Second Exercise*, Cologne
Cage, J., *Fontana Mix*, Milan
Cambier, R., *Jeune Fille et l'Étoile*, Paris
Carvalho, R. *Estudio I: vidro*, Rio de Janiero
Cary, T., *The Diary of a Madman*, London
Cary, T., *The Little Island*, London
Cunningham, J., *Suite in the Form of a Mushroom*, Chcago
Cunningham, J., *Tic Toc Fugue*, Chcago
Dissevelt, E. *Syncopation*, Hilversum
Dissevelt, E. *Whirling*, Hilversum
Dufrne, F., *Batteries vocales*, Paris
Dufrne, F., *Crirhythme de St.-Sylvestre*, Paris
Dufrne, F., *Élettrisation*, Paris
Dufrne, F., *Paix en Algérie*, Paris
Dufrne, F., *Petit hommage à l'année 1955*, Paris
Dufrne, F., *Un Opéra de Pékin à Paris*, Paris
Eimert, H., *Variante einer Variation von Anton Webern*, Cologne
Engelmann, H.U. und O. Sala, *Der Sturm*, Berlin
Ferrari, L. and P. Schaeffer, *Continuo*, Paris
Ferrari, L., *Capricorne*, Paris
Ferrari, L., *Échantillons*, Paris
Ferrari, L., *Étude aux accidents*, Paris
Ferrari, L., *Étude aux sons tendus*, Paris
Ferrari, L., *Étude floue*, Paris
Ferrari, L., *L'Égypte à l'Égypte*, Paris
Gerhard, R., *All Aboard*, Cambridge GB
Gerhard, R., *Pericles*, Cambridge GB
Gerhard, R., *Your Skin*, Cambridge GB
Guttman, N., *Pitch Variations*, Murray Hill, N.J.
Hambraeus, B., *Reaktion*, Stockholm
Hambraeus, B., *Tidsspegel*, Stockholm
Heidsieck, B., *Poème-Partition A*, Paris
Heidsieck, B., *Poème-Partition C2*, Paris
Heidsieck, B., *Poème-Partition D*, Paris
Heidsieck, B., *Poème-Partition D2*, Paris
Heiss, H., *Die Tat*, Darmstadt
Heiss, H., *Essay II*, Darmstadt

Henry, P., *Ariane II*, Paris
Henry, P., *Bronze*, Paris
Henry, P., *Coexistience*, Paris
Henry, P., *Intermezzo*, Paris
Henry, P., *Orphée*, Paris
Higgins, D., *A Loud Symphony*, New York
Higgins, D., *Graphis 24*, New York
Kagel, M., *Transición*, Cologne
Klebe, G., *Menagerie für Orchester und Tonband*, Berlin
Koenig, G.M., *Essay*, Cologne
Kotonski, W., *Albo rybka*, Warsaw
Le Caine, H., *A Noisesome Pestilence*, Ottawa
Le Caine, H., *Textures*, Ottawa
Le Caine, H., *The Burning Deck*, Ottawa
de Leeuw, T., *Studie*, Hilversum
Ligeti, G. *Artikulationen*, Cologne
Ligeti, G., *Pièce électronique nr. 3* (score only)
Luening, O. and V. Ussachevsky, *Back to Methuselah*, New York
Luening, O., *Dynamophonic Suite*, Paris
Maderna, B., *Continuo*, Milan
Maderna, B., *Musica su due dimensioni II*, Milan
Markowski, A., *Histoire d'un avion de chasse*, Warsaw
Maroi, M., *Metamorphosis*, Tokyo
Mumma, G., *Ritmi*, Ann Arbor
Mumma, G., *Soundblock 4*, Ann Arbor
Mumma, G., *Soundblock 5*, Ann Arbor
Mumma, G., *The Bald Soprano*, Ann Arbor
Mumma, G., *The Image in Time*, Ann Arbor
Ooki, H., *Concertant Four Movements*, Kamakura
Pade, E.M., *Glasperlespil I*, Copenhagen
Pade, E.M., *Glasperlespil II*, Copenhagen
Pade, E.M., *Seven Circles*, Copenhagen
Pade, E.M., *Symphonie magnétophonique*, Copenhagen
Parmegiani, B. *IFI*, Paris
Parmegiani, B. *Visage d'Afrique*, Paris
Philippot, M., *Les Orphelins*, Paris
Pousseur, H., *Étude pour Rimes II*, Brussels
Pousseur, H., *Liège, cité ardente*, Brussels
Pousseur, H., *Sémaphore*, Brussels
Radauer, I., *Spiel um Job*, Salzburg
Riedl, J.A., *Ermüdung*, Munich
Riedl, J.A., *Studie für Elektronische Klänge*, Munich

Sala, O., *Aluminium: Porträt eines Metalls*, Berlin
Sala, O., *Du hast die Chance*, Berlin
Sala, O., *Forschung und Leben*, Berlin
Sala, O., *Gefahr Nordwest*, Berlin
Sala, O., *Kompositionen für Mixturtrautonium*, Berlin
Sandloff, P., *Der Meisterdieb*, Berlin
Sassi, R., *Le navigateur*, Geneva
Schaeffer. P., *Étude aux allures*, Paris
Schaeffer. P., *Étude aux sons animés*, Paris
Sekorski, J., *Prowiesc pravie o koncu swiato*, Warsaw
Sheff, R., *Chorales*, San Antonio Texas
Takemitsu, T., (Without title), Tokyo
Takemitsu, T., *Dialogue*, Tokyo
Takemitsu, T., *Sky, Horse, Death*, Tokyo
Taleoff, D., *Tribulation*, Berkeley
Taleoff, D., *Trilogy in two channels*, Berkeley
van Thienen, M., *Nutrition des Plantes*, Mareil-en-France
van Thienen, M., *Sahara brut 58*, Mareil-en-France
Thärichen, W., *Musik auf Pauken*, Berlin
Toulier, J.-P., *Wenceslas*, Paris
Ussachevsky, V., *Linear Contrasts*, New York
Varèse, E., *Poème Électronique*, Eindhoven
Vivier, O. *Séquences rhythmiques*, Paris
Vlad, R., *Requiem for a Nun*
Wisniewski, Z., *Orphée*, Warsaw
Wolman, G.,J., *Le monologue intérieur*, Paris
Xenakis, I., *Analogique B*, Gravesano
Xenakis, I., *Concret P. H.*, Paris
Xenakis, I., *Dimorphoses*, Paris
Zumbach, A., *C'est arrivé l'année prochaine*, Geneva

6 Time in Electroacoustic Music

Time passes differently in electroacoustic music than in instrumental music. Instrumental and vocal music in general is metrical in nature, conceived on a framework of regularly recurring pulses. Both the large-scale formal organization of metrically structured music and the fine nuances of individual interpretation articulate themselves in relation to this regular framework. Much electroacoustic music, on the other hand, has no meter but unfolds instead on a background of chronological time.

It is difficult to be sure what difference the a-metrical quality of electroacoustic music makes to its perception. One important difference certainly lies in the fact that the symmetrical structures of traditional music are missing in electroacoustic music. The ear, or more precisely the brain, is much less adept at measuring temporal differences than at measuring differences in frequency and pitch.[15] Regular meter makes organization into groups of equal or comparable length (two and two beats, two and two measures, eight and eight measures, etc.) possible for the perception. Here metrical time predominates over chronological time, for two phrases of the same metrical length may have very different actual durations, depending upon how they are played, and still be heard as being equivalent. Metrical time is structured by a regularity outside and independent of the perception, the recurrent pulse,[16] whereas chronological time is structured by the perception itself, by its judgments of apparent fullness or emptiness, and by fulfillment or nonfulfillment of expectation. Metrically organized music presents itself to the perception in a more objective guise than does music which is not organized metrically, or where the metrical organization is intentionally obscured.

It is interesting to look for a moment at differences in the way time passes in classical and romantic instrumental music, before turning to electroacoustic music. In the music of Haydn and Mozart, and of the Vienna Classical Period in general, the measure is the basic rhythmical building block: groups of four and eight measures are the norm, but the most interesting music constructs phrases of irregular length, whose deviation from the expected norm is part of their expressive content. Fifty and sixty years later, the expressive, intimate music of Chopin and Schumann differs fundamentally from that of Haydn and Mozart in that larger phrases no longer show this variation in length but are very often with relentless regularity eight measures long. Within these eight measures, however, the actual rhythmic structure is often quite complex: several different systems of accent frequently overlap (metric, rhythmic, melodic, harmonic), resolving their differences only at the end of the phrase.[17] Much music at the beginning of this century—Debussy's *Pelléas et Mélisande* or the expressionistic atonal music of Schoenberg, Webern and Berg—show this concern with avoiding metrical clarity in a much more exaggerated way. It is difficult to evaluate the expressive function of this rhythmic complexity, but if one asks how the music would be different if overlapping of accent did not occur, it is clear that the pieces would be less particular, less personal, more banal and clumsy, closer to popular music. The rhythmic complexity serves principally to weaken the influence of the metrical accent by dividing stress more equably among the metric units (beats and half-beats). But the syntactical function of accent is to mark the flow of sound, to divide it into segments with which the perception can deal more easily. If these divisions become ambiguous, or disappear altogether, the perception can still deal with the music perfectly well (at least in retrospect; Schumann is not more difficult for us than Mozart, but Mozart's contemporaries would certainly have been astonished at Schumann on first listening), but the quality of the music changes: it seems to speak more intimately and personally. Perhaps some mode of perception changes. Perhaps we recognize an analog to our own thoughts and emotions as they are before we are able to formulate them clearly; Joyce's rejection of punctuation and syntactical aids to subdividing Molly Bloom's soliloquy at the end of *Ulysses* achieves precisely this effect with techniques similar to those used in music.

Electroacoustic music (along with serial music and, in a somewhat different way, much minimal music) carries this tendency to suppress meter much further, usually doing away with it altogether. Not only is meter usually missing from electroacoustic music, but so are physical characteristics of sound production, like breathing, or acoustical clues to how the sound was made, which would help establish some link to more familiar music. The upshot of all this is that electroacoustic music generally feels the opposite of "intellectual"; far from being perceived as inhuman and technological, it is usually experienced directly and with an emotional immediacy of which little instrumental music can boast.

Many techniques in electroacoustic music support this vision of time as unregulated flow. The tape itself, on which, historically at least, an electroacoustic composition takes definitive form, is a physical embodiment of the flow of chronological time. Sound can be generated by making loops of pieces of prerecorded tape which have no beginning and no end, by turning on an oscillator whose signal could go on for ever or by combining segments of relatively simple sonorous structure to form complex textures without clear beginning or end. Pieces can be thought of as great Copernican systems with cycles and epicycles of continuous sound, only small parts of which are actually audible. Because of this close correspondence between the flow of time and the materials and instruments of electroacoustic music, electroacoustic techniques have had considerable influence on contemporary instrumental music. A major theoretical task of serial music in the 1950's was to find new paths of larger-scale formal organization of a composition. The tape music of the epoch presented the same problem, but, whatever form the theoretical solution might take, it had very straightforward consequences in tape music: pieces of tape of specific lengths had to be cut and reassembled in a certain order. The obvious way to deal with these fragments was to order them in systems of proportional duration (always correlated to the physical length of the pieces of tape[18]). Many composers who experienced the physical manifestation of chronological time in working experimentally with tape music in the 1950's continued working with proportion in their instrumental music. The temporal structuring of the music of Ligeti or of the composers of the Polish School of the 1960's (Lutosławski, Dobrowolski, Penderecki, et al.) depends directly upon these composers' experiences with tape music. It seems safe to suppose that the collective experience of many composers with electroacoustic music since 1950 or so—even if individual experiences were disappointing or inconclusive—has contributed decisively towards changing the way we think of musical time today.

7 Sound Synthesis

One of the most seductive aspects of electroacoustic music for a composer is its potential sonorous richness. There is literally no limit to the new sounds which can be constructed, either from scratch or by transformation of existing "natural" sounds. But just as there is no limit to the new sounds possible, neither is there any very obvious way to order families of new sounds. The serial music of the 1950's dreamt of structuring the timbre of sound with the same precision as the twelve chromatic tones, but not only was it fairly difficult to construct interesting sounds in the first place, in addition it usually turned out that the criteria used for generating the sounds and which might seem to be appropriate for ordering them were of no perceptual relevance whatsoever. Even today, after more than forty years of electroacoustic music, and after at least a generation of psychoacoustic research specifically centered on the question of timbral perception, the theoretical results are meager at best. As a result, sound synthesis and transformation techniques are usually discussed in technical terms rather than from a perceptual point of view.

Traditionally, there are two main types of sound synthesis, regardless of the instruments used for the synthesis: additive synthesis and subtractive synthesis. Additive synthesis begins with simple sounds and combines them to achieve complex results, subtractive synthesis begins with a rich spectrum, for example noise, and moves towards a somewhat more selective complexity by filtering. Subtractive synthesis has historically been an important technique, because it offers fairly precise control over the resultant sound, while allowing an arbitrarily rich spectrum of the material to be filtered. Until the appearance of digital sound processing techniques, subtractive synthesis was somewhat restricted because of the expense of high-quality filters offering the flexibility composers sought. Since the appearance of digital filtering techniques, which have made possible the dynamic use of filters of all types with great precision and flexibility, at least in non-real-time software synthesis, subtractive synthesis has been somewhat restricted by the relatively long computation times required for digital filters. Nonetheless, subtractive synthesis still remains an important, well-understood and, in its application, intuitively straightforward and elegant technique.

Strictly speaking, additive synthesis refers to the building of complex sounds by the addition of individual partials, each having its own frequency and amplitude pattern. I am assuming considerable license in grouping together here all those synthesis techniques which create complex sounds from simple elements. The instruments originally used in electroacoustic music to generate sound produced their oscillations and pulse trains physically: electrical components imposed upon an electrical current the form of the sound wave one wished to model; this current was then amplified and sent to loudspeakers. One speaks here of "analog" technology: the electrical current produced is a physical analog of the sound wave desired. But very small differences in temperature or in the characteristics of the physical material making up the components could cause audible changes in the sound produced; in addition, these instruments were difficult to calibrate exactly, and so it was often impossible to find precisely the settings one had used the day before. Contemporary electroacoustic instruments use almost exclusively digital techniques for sound generation. In digital instruments, the result of every operation is a string of numbers which must first be converted into changing electrical current before a sound can be heard. Digital instruments are very precise, and since they can be exactly calibrated, results can be reproduced from one day, or from one year, to the next. Analog instruments carry out their operations instantaneously. What they may lack in precision, they compensate for in directness of use: turning a knob affects the sound directly, and one has a tactile relationship with the sound, not so intimately as would be the case with a violin or a clarinet, to be sure, but using analog instruments it is certainly possible to impose physical gesture on electroacoustic sound. Digital instruments do not carry out their operations instantaneously (see note 10 et passim) but rather as a function of both the basic speed of the device and the complexity of the operation to be carried out. Some operations are simple enough that the user has the impression of instantaneous sound production, many are not.

A perverse law of sound synthesis would seem to put the degree of control which one can exercise over a sound directly proportional to the difficulty of its computation. The example of the technique of synthesis by frequency modulation is instructive here. Additive synthesis was the first technique used for digital sound synthesis. Constructing sounds by additive synthesis, specifying frequency and amplitude patterns for each of from fifteen to thirty partials for every sound, offers composers extremely fine control over the spectral structure and evolution of their music. But deriving all this information and communicating it to the program doing the synthesis is not a trivial task, nor is the computation time to be ignored.[19] Composers began looking for other synthesis techniques which would be more economical both in terms of preparation and in terms of computation time. The best known alternative to additive synthesis is synthesis by frequency modulation. The simplest frequency modulation (FM) is very economical to calculate, requiring somewhat less computation time than two partials of additive synthesis, but easily capable of producing spectra of great complexity having very many partials. It can easily produce sounds having dynamically changing spectra, and it can very easily control (or vary dynamically) the degree of harmonicity of the sound (i.e., whether the partials produced are in harmonic relationship to one another or not). In general, however, it is very difficult to model a specific spectrum, to place energy precisely where one wishes, because of the way the frequency modulation algorithm apportions the available energy. And if it is difficult to model a single spectrum using FM, it is virtually impossible to define freely the trajectory a sound's timbre will take in progressing from simpler to richer quality; here again, it is the algorithm which prescribes exactly what amplitudes the partials will have at a given moment; the progression cannot be influenced, the timbral change is determined by the mathematics which make the algorithm economical in the first place. The behavior of the frequency modulation algorithm is typical of all techniques of wave distortion: simple manipulations produce complex spectral results, but the user has little control over the actual form of the spectrum. Once again, as the approximate benchmark values in note 19 confirm, the degree of control one can exercise over the spectrum of the sound is directly proportional to the computation time.

Although the classical digital sound synthesis programs (for example Music V, CSound, CMusic) offer virtually unlimited possibilities for synthesis, the discovery of new algorithms for synthesis remains an important field of research for composer and scientist. There are doubtless many algorithms yet to be discovered which are computationally simple and economical and which give spectrally rich and interesting sounds (the so-called Karplus-Strong technique for synthesizing the sound of plucked strings is a good example), but in general new synthesis algorithms should be conceived to work in the frequency domain, that is, the composer should define spectral characteristics and the algorithm should take care of the translation necessary to synthesize the time-variant pressure wave to be sent to the loudspeaker. (Of the techniques listed in note 19, numbers 3, 4, 7 and 8 present themselves in the frequency domain.) The difficulty here is that the translation from frequency to time domain, or vice versa, is computationally costly. Hence, programs offering direct spectral manipulation are likely to remain cumbersome and slow, at least until mathematicians and physicists find new ways to link the time and frequency domains.[20]

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Notes

[1]The principal early studios were: the Club d'Essai (Pierre Schaeffer) in Paris, 1948 (which became the Groupe de Recherche de Musique Concrète in 1951 and the Groupe de Recherches Musicales in 1958), the Columbia–Princeton Electronic Music Center (Vladimir Ussachevsky, Milton Babbitt, Edgard Varèse et al.) and the Studio für Elektronische Musik in Cologne, both in 1951, the Studio di Fonologia of the Radio Audizioni Italia (RAI) in Milan (Luciano Berio, Bruno Maderna) in 1953, the Philips Research Laboratories (Henk Badings) at Eindhoven in 1956, the Studio Eksperymentalne of the Polish Radio in Warsaw in 1957, the San Francisco Tape Music Center in 1959.

[2]The exposition *Nuova Atlantide—il Continente della Musica Elettronica 1900–1986* organized by the Venice Biennale, which offered a fascinating retrospective of electroacoustic music during this century, chose as motto Francis Bacon's description of the Sound House from the utopian *New Atlantis* (1627).

[3]The degree of earnestness—the *sérieux*—of electroacoustic music in Germany is a theme which is still of interest today. It is quite remarkable that in such a rich European country, where on the one hand the most advanced technology is easily available, and where so much contemporary music is written and performed, on the other, there has been—since the decrease in importance of the Cologne studio—so little electroacoustic music. One hypothesis seeks to put contemporary activity in the perspective of the humanistic intellectual tradition of German music in the 18th and 19th centuries, whose great achievement was to render audible and public a world of emotion both conscious and—at least after Wagner—consciously unconscious, which neither literature nor painting nor any other artistic endeavor had hitherto tapped. German composers today, so runs the hypothesis, remain faithful to this tradition and seek the articulation of a contemporary musical language not in combination with technology, but rather in a more spiritual—*geistig*—plane. The rejection in 1969 of a proposed Institute for Musical Research by the Max-Plank-Gesellschaft, where financing and personnel were not central issues, seems to support the hypothesis. It would be interesting to read carefully the propaganda issued for some time supporting the creation of a new *Zentrum für Kunst und Medientechnologie* (Center for Art and Media Technology) in Karlsruhe to see whether the arguments used would support the hypothesis. In Japan, where contemporary composers frequently describe the established musical cultures, both Japanese and occidental, as sentimental, there is

also surprisingly little electroacoustic music. One explanation given is that the ubiquity of technology in everyday life accentuates the desire for "sentimental" traditional music.

[4]Revue Musicale, Paris (Richard-Masse), 1957, no. 236.

[5]Although this discussion applies more directly to Schaeffer's *musique expérimentale*, it is equally valid for *elektronische Musik*, which was from the beginning closely linked to serial music. The addiction to a kind of general chromaticism extending over all aspects of a piece of music, the need for constant change combined with an exquisitely fine sense of recognition of sounds or structures already heard were frequent by-products of composition with serial techniques. Of course, the same tendency is a principal moving force behind the development of the music of A. Schoenberg, A. Webern and A. Berg between about 1908 and 1923, when Schoenberg began to practice his theory of composition with 12 tones.

[6]The first synthesizer-like electronic instrument was probably Hugh LeCaine's Electronic Sackbut built in Ottawa between 1945 and 1948. Perhaps the first electroacoustic instrument at all (whose sound was produced electronically, in contrast to the many musical instruments built in the last quarter of the 19th century with electrically assisted mechanical actions for producing sound acoustically) was the Telharmonium or Dynamophone, built by Thaddeus Cahill in 1906 in Massachusetts and New York.

[7]Moog tells this story in the *Procedings of the Colloquium of the Confédération Internationale de la Musique Électroacoustique "Pourquoi ai-je fait cela, et comment"*, held in Bourges, France, in June 1989, forthcoming.

[8]Another interesting example is the licensing of the patent for sound synthesis by frequency modulation from Stanford University by Yamaha. John Chowning, working in very informal and difficult conditions on the periphery of the Artificial Intelligence Laboratory of Stanford University, experimented with the technique of frequency modulation, well understood from radio transmission, and found it adaptable to the synthesis of complex sound spectra (Chowning's paper was published in 1973). Subsequent research established the theoretical underpinnings on which composers could base a sophisticated and subtle use of the technique, mostly in non-realtime sound synthesis. Later Yamaha licensed the patent for this technique (not without encouragement from Chowning and his group and Stanford University) and used frequency modulation in many of their synthesizer series from the early 1980's on. The version of the frequency modulation technique realized by Yamaha performed the synthesis in real time but offered only a very reduced subset of the possibilities of the technique. But the programming of even this subset proved too difficult to master for most synthesizer customers, who only wanted some instrumental sounds anyway, and soon a great traffic in "patches"—pre-programmed settings—for the synthesizers arose. And so the experimental, innovative work on frequency modulation found a watered-down, distorted representation in hundreds of thousands of private studios.

[9]Lev Termen (Leon Teremin) built his first instrument in Moscow in 1919; it was successively named the Aetherophon, the Termenvoks and the Theremin. Maurice Martenot demontrated his first instrument in Paris in 1928. Friedrich Trautwein built the Trautonium in 1930; Oskar Sala's extension, the Mixtur-Trautonium, dates from 1949-1952.

[10]This is a rather technical note. Specialized digital signal processors controlled by general-purpose computers have been around for some time. They offer rapid calculation but have physical limits to the number of operations per second they can

carry out (or, if these limits are very high, then the machines are so expensive as to be virtually unusable). Only recently have relatively inexpensive digital signal processors controlled by microcomputers become available which may be able to do fairly complex synthesis in real time. It is important to recognize however that the physical limits are not a trivial annoyance, but an intimate characteristic of the numerical generation of sound; nor are they likely to be overcome in the near future simply by increasing calculation times by a factor of 100 or so. An example: A computer program known as the Phase Vocoder allows the modification of a pre-recorded sound in the frequency domain rather than the time domain, as is usual. So for example the sound can be transposed without changing its duration or can be filtered as sharply as one wishes without introducing distortion of phase, two operations which are not usually feasible. On an Atari 1040 16-bit computer running at 8 Mhz the Phase Vocoder can require 60,000 seconds and more to process one second of recorded sound at high resolution. It would be very interesting to carry out these operations in real time so that instrumental sounds could be modified in concert. If one agrees to limit oneself to a maximum of five simultaneous voices—hardly an exorbitant demand—the ratio of calculation time to real time would still be at least 300,000 to 1 (or 83 hours and 20 minutes for one second of sound). Even if one would admit various compromises—calculating in fixed point form rather than floating point form, less frequency resolution, etc.—, it seems doubtful that the acceleration one would need could be achieved easily. Clearly, certain synthesis algorithms are very efficient in relation to the spectral complexity obtained (frequency modulation is a good example, as are so-called waveshaping algorithms in general, granular synthesis, etc.); some of these have already been realized in commercial synthesizing machines. But what one is after is more general software synthesis. In any case, there will always be physical limits to the complexity of digital synthesis and processing possible in live electroacoustic music dictated by the limits of calculation speed.

[11]This is another technical note. Samplers use one of two techniques for transposition. Many samplers vary their sampling rate as they read a sound out. The varying sample rate implies having a variable-frequency smoothing filter follow the transposition. This technique requires separate digital-to-analog conversion and filtering after conversion for each of the output channels of the sampler. The potentially more elegant technique is to read through the stored sounds at different rates, outputting the samples at a fixed sample rate. A great improvement in the quality of the sound (and the precision of the frequency obtained) can be achieved by interpolating between two successive values of the stored wave form; however, interpolation places a certain burden of calculation on the hardware. Some newer samplers oversample at record time, which allows them to do without interpolation and still achieve good sound quality (at the cost of memory space). This second variable-rate table-look-up method requires digital-to-analog conversion only of the final result, which may be the sum of several sounds.

[12]Yet another technical note. Sound is represented digitally by a stream of numbers representing instanteous amplitude values at very small intervals of time; this representation of amplitude versus time is called the "time domain". The ear, however, analyzes sound into frequencies of specific amplitude. This representation of amplitude versus frequency, which is intuitively and perceptually the more relevant, is called the "frequency domain". Traditional musical notation is in the frequency domain. Two techniques which permit work in the frequency domain are Linear Predictive Coding and the Phase Vocoder, mentioned above. Linear Predictive Coding may be thought of as a system of filters, through which a pre-recorded sound is passed, and which notates the evolution of a coefficient for each of typically five hundred to one thousand filters over the duration of the sound. The original sound can be resyn-

thesized, or depending upon coefficient values and the excitation used for the filter system transformed sound can be synthesized. The Phase Vocoder calculates the amplitudes of the frequency components directly using the Fast Fourier Transform. These amplitudes can be manipulated straightforwardly, and the transformed sound can be resynthesized using the Inverse Fourier Transform. It is conceptually easy to transpose speech and to maintain the original resonance structure, but formidable calculating power is required, as it is with Linear Predictive Coding.

[13]Very little is known about the long-term shelf-life of magnetic audio tape. One of the problems of the electroacoustic music of the 1950's is that the original tapes are losing their magnetization and the music is disappearing. Digital recording offers potentially better storage because minor random physical deterioration of the magnetic coating does not immediately affect the sound. But even less is known about the shelf-life of the magnetic media used for digital recording. At present, the compact disc seems to promise virtually unlimited conservation in relatively high quality.

[14]This list is largely taken from: *Répertoire International des Musiques Électroacoustiques*, compiled by Hugh Davies, Paris (Le Groupe de Recherches Musicales de l'O.R.T.F. / The Independent Electronic Music Center Inc.), 1968.

[15]Actually, the brain is extraordinarily good at measuring very small temporal differences, those in the millisecond range. It can resolve successive actions having a duration of 40 to 50 milliseconds or longer (between 25 and 20 Hz) into individual events. In fact, my peripheral vision can see something of the 69 Hz (period of 14.5 milliseconds) flicker of the refreshing of the monitor screen on which I am writing this text. The ear can differentiate without any difficulty between a sound having an attack time of 5 milliseconds and one having an attack time of 10 milliseconds. Much of the information the ear receives about the reverberation time and quality of a room, particularly a small room, arrives within 40 milliseconds of the direct sound; strong echoes received later than 40 milliseconds after the direct sound make the resultant sound unclear.

[16]Most Western music has more than one level or recurrent pulse: slowly moving pulses, for example the measure itself, and more rapidly moving ones, for example the beats within a measure. The beats are marked (in the linguistic sense) for hierarchy by accents (so, for instance, in four-four measure the first and thrid beats are generally more strongly accentuated than the second and fourth beats). Other music, especially in this century, builds its rhythms from a small, rapid pulse, a sort of lowest common denominator (often an eighth or a sixteenth note). Here it is sometimes difficult to feel the pulse, but it serves as strongly an organizing function as in more traditional music.

[17]The reader who is interested in pursuing further the question of rhythmic counterpoint in romantic music should look at "Wehmut" from *Liederkreis* (Eichendorff) op. 39, or the first of the *Gesänge der Frühe* op. 133 by Robert Schumann, or the *Nocturnes*, for example op. 27 No. 1, by Fréd'eric Chopin, to choose virtually at random from among many works showing this characteristic way of working. At certain times, rhythmic polyphony has been the rule rather than the exception. The vocal polyphony of the entire 15th century, for example, is characterized by the greatest rhythmic independence of the individual voices.

[18]So, for example, 370.5 cm [9.75 seconds] of Sound A could be spliced onto 599.5 cm [15.78 seconds] of Sound B, the two sounds being related in length to each other as the Golden Mean, always assuming that the tape passes through the magnetophone at 38 cm per second. Electroacoustic music also offers the possibility of linking the

"horizontal" temporal dimension of music more intimately with the "vertical" pitch or frequency dimension. If one uses a variable speed magnetophone to accelerate Sound B so that it lasts exactly as long as Sound A, then Sound B will have been transposed up by the Golden Mean. In this way, formal relationships between time and pitch can be established.

[19]If the calculation time required to synthesize a sound having a single partial of fixed frequency and amplitude is 1, then the following approximate values were obtained for other synthesis operations for a sound of the same length, using one of the well-known programs of sound synthesis:

1. One partial, varying amplitude and frequency: 2
2. Karplus-Strong synthesis of one plucked string: 3
3. Subtractive synthesis, using white noise, one second-order filter, fixed frequency and bandwidth: 2.5
4. Subtractive synthesis, using white noise, one fourth-order filter, variable frequency and bandwidth, output amplitude adjusted to input amplitude: 9
5. One simple FM unit, varying modulation index, modulating frequency and amplitude, fixed carrier frequency: 3.6
6. Fifteen partials, each with varying amplitude and frequency: 28
7. Five formants in FOF-synthesis (forme d'onde formantique), all parameters fixed, fundamental frequency 100 Hz (the calculation time increases linearly with the fundamental frequency): 170
8. Analysis and resynthesis using the Phase Vocoder algorithm, 512 filters: 218

The techniques are arranged according to approximate ease of spectral manipulation. These proportions should be approximately valid for all programs of software synthesis. (The synthesis using variable values represents worst-case situations. Usually it should be possible to design the synthesis so as to reduce significantly the calculation time required for these variables.)

[20]Jean Baptiste Joseph Fourier (1768-1830), after 1808 Baron de Fourier, showed mathematically how reasonably periodic vibration could be uniquely decomposed into a sum of simple vibrations of specific and fixed frequency, amplitude and phase. These mathematical relationships still today form the basis of the translation between the time and the frequency domains. There may be other laws for expressing completely the interdependency of these two domains. Recently a research group under Jean-Claude Risset at the Centre National de Recherche Scientifique at Marseille has investigated analysis and resynthesis of sound waves using a model different from that of Fourier, *l'analyse par ondelettes*, analysis by wavelets, first suggested by the geophysicist Jean Morlet in 1983; preliminary results seem very promising. One advantage of this new technique is its computational economy, compared with Fourier analysis.