Iannis Xenakis

MUSIC COMPOSITION TREKS


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Musical Universes

The universes of music–classical, contemporary, pop, folk, traditional, avantgarde, etc.–seem to form units within themselves, sometimes closed, sometimes interpenetrating. They present amazing diversities, rich in new creations but also fossilizations, ruins, wastes, all in continuous formation and transformation like the clouds, so differentiated and ephemeral.

This is explained by the proposition that music is a sociocultural phenomenon subordinated to a given instant in history. However, one can distinguish parts that are more invariant than others and thus form materials of hardness and consistency, resulting from diverse epochs of civilizations, materials that move in space, created, hurled, and driven by currents of ideas, clashing, influencing, annihilating, and fecundating each other.

But of what essence are these materials made? This essence is the intelligence of man solidified in a way: intelligence that seeks, questions, infers, reveals, and foresees at all levels. Music and the arts in general seem necessarily to be a solidification, a materialization of intelligence. Naturally, this intelligence, though humanly universal, is diversified by the individual, by talent that distances one individual from the others. Talent is therefore a kind of qualification, a gradation of the vigor and richness of intelligence. For intelligence is, fundamentally, the result, the expression of billions of exchanges, of reactions, of transformations of energy in the cells of the brain and the body. One could, taking astrophysics as a visual aid, say that intelligence is the form taken by the minimal acts of cells in their condensations and their movement, as happens with the particles of the suns, planets, galaxies, and clusters of galaxies born of or turned back into cold interstellar dust. This image, however, is reversed (at least at one level) because this could result in exchanges between the hot cells of the brain and of the body–a "cold fire".

It results that music is a strong condenser, perhaps stronger than the other arts. It is for this reason that I give a table of comparisons between certain conquests of music and several realizations of mathematics taught to us by history (see Appendix A). This table shows one of the paths that music has taken since its origin (since Antiquity) and that has held with remarkable fidelity through millennia with a strong acceleration in the twentieth century. This proves that, far from being a fashion, this faculty of condensation toward abstraction is of a profound nature that belongs to music no doubt more than to other arts. Consequently, it seems that a new kind of musician is necessary, that of the artist-conceiver of free and abstract new forms, tending toward complications and generalizations at several levels of sound organization. For example, a form, a construction, an organization built on Markovian chains or on a complex of interlocked probability functions may be carried over simultaneously onto several levels of musical micro-, meso-, and macrocompositions. One can also extend this remark to the visual domain -for example, in a *spectacle* made out of laser beams and electronic flashes of the *Polytope of Cluny* and the Diatope of the Centre Georges Pompidou.

Nothing prevents us from foreseeing from now on a new relationship between the arts and sciences, particulary between the arts and mathematics, in which the arts would consciously "pose" problems for which mathematics ought to and must forge new theories.

The artist-conceiver will have to possess knowledge and resourcefulness in domains as varied as mathematics, logic, physics, chemistry, biology, genetics, paleontology (for the evolution of forms), human sciences, and history–in short a kind of universality, but a knowledge founded, oriented by and toward forms and architectures. It is also time to found a new science of *general morphology* that will deal with forms and architectures of these diverse disciplines, studying their invariant aspects and the laws of their transformations, which have in some cases lasted millions of years. The backdrop of this new science should be the real condensations of intelligence–that is, the abstract approach cleared of the anecdotes of our senses and habits. For example, the formal evolution of the vertebrae of dinosaurs is one of the paleontological documents to add to the dossier of the science of forms.

Let us plunge now into the fundamental system on which art rests. Art has something in the nature of an inferential mechanism, which constitutes the ground on which move all the theories of mathematical sciences, physics, and those of living beings. Indeed, the games of proportions reducible to games of numbers and metrics in architecture, literature, music, painting, theater, dance and so on–games of continuity, of proximity, in- or outside of time, of topologic essence–are all made on the terrain of the inference, in the strict logical sense. Besides this terrain exists the experimental mode that challenges or confirms the theories created by the sciences, including mathematics. Since the development of non-Euclidean geometries and the theorem of Goedel, mathematics has also proven to be an experimental science, but over a longer time span than the other sciences. The experiment makes and breaks theories, without pity and without consideration for them. Now, the arts are also governed, in a manner still more rich and complex, by the experimental mode. Indeed there are not, and without a doubt never will be, objective criteria for absolute and eternal truths of validity of a work of art, just as no scientific "truth" is definite. But in addition to these two modes of activity–inferential and experimental–art lives in a third, that of immediate *revelation* that is neither inferential nor experimental. The revelation of beauty is made at once, directly, to the person ignorant of art just as to the connoisseur. Revelation makes the force of art and, it seems, its superiority over the sciences because, living in the two dimensions of the inferential and experimental, art possesses this third possibility, the most mysterious of all, the one that makes the objects of art escape any aesthetic science all the while indulging in the caresses of the inferential and the experimental.

But on the other hand, art cannot live only by means of revelation. Art must have, as shown to us by the history of art of all times and all civilizations–indeed, it has an imperious need of–organization (including that of randomness), therefore of inference and of its confirmation, therefore of its experimental truth.

The two modes of inference and experimentation are today almost always closely related to the computer. Just as the wheel was once one of the greatest products of human intelligence, a mechanism that allowed one to travel farther and faster with more luggage, so is the computer, which today aids the transformation of human ideas. Computers resolve logical problems by heuristic methods. But computers are not responsible for the introduction of mathematics into music; rather, it is mathematics that makes use of the computer in composition. Yet if people's minds are in general ready to recognize the usefulness of geometry in the plastic arts (such as architecture and painting), they have only one mote stream to cross to be able to conceive of using more abstract, non-visual mathematics and machines as aids to musical composition, which is more abstract than the plastic arts.

Since World War II, computer science has invaded the domain of human activities. The arts, and in particular music, have not been overlooked by this tidal wave. Slowly in the 1950s, then accelerating, the computer and its peripherals have been spreading like mushrooms in the centers of musical activity, upsetting the attitudes of composers to a far greater extent than did the revolution of the tape recorder, which originated the first physically permanent memory of sound. The danger is great of letting oneself be trapped by the tools and of becoming stuck in the sands of a technology that has come like an intruder into the relatively calm waters of thought in instrumental music. For we already have a long list of attempts at composition by the computer. But what is the musical quality of these attempts? It has to be acknowledged that the results from the point of view of aesthetics are meager and that the hope of an extraordinary aesthetic success based on extraordinary technology is a cruel deceit. Indeed, little of this music goes beyond the recent rich findings in instrumental music or even beyond the babblings of electronic music in the 1950s.

Why? In my opinion, the reasons for these failures are multiple, but we can single out two essential ones:

1. The musicians using computers are cripples in general theoretical ideas, especially in mathematics, physics, and acoustics. Their talent, whenever it exists, is powerless in penetrating the virgin domain where only abstract thought would be capable of guiding their experimental attempts, and it grasps but mere shadows.

2. Scientists who have access to computer technology are sucked in by a sort of inferiority complex when facing the aesthetic aspect of music and, not having had to struggle on the aesthetic plane, are inexperienced and lacking and have no idea where they should be heading. Consequently, they fool around with mathematical and technical gadgets with the net musical result of very little, if any, artistic interest since they are notable, and do not know how to employ talent when they have it.

In these two cases, artistic talent, as it can clearly be seen, plays–and must play–a determining role.

To escape from these impasses, the remedies are obvious: the first category of musicians should make an apprenticeship in the necessary sciences, and the second category should plunge into the delicate questions of talent and aesthetics, constantly experimenting with them by composing. But this will not suffice. It seems to me that the moment has come to attempt to penetrate more profoundly and at the same time more globally into the essence of music to find the forces subjacent to technology, scientific thought, and music.

I am now going to confine myself to sketching a single line of approach–since there are many–that appears to me to be very important. Indeed, research in the coming years must explore diverse levels, from microcomposition, which deals with sound synthesis starting from durations of the order of the microseconds (one millionth of a second), all the way to macrocomposition, which treats musical discourse for durations in terms of hours.

The methods and theoretical approaches may be distinct according to one level, or they may be used át more than one level. To throw more light on the problem, we are going to discuss two near-extreme levels: microcomposition and macrocomposition in the above defined sense, by giving central ideas that serve as springboards for the coming years of research and composition aided by computers.

Macrocomposition

a. Explore compositions starting from the marcoscopic ST(ochastic) program in FORTRAN (published in *Formalized Music*, 1971, Indiana University Press), which is stochastic in orientation and uses sound elements (1) of orchestral instruments, (2) designed on the UPIC[1], and (3) produced by the methods and theories of microcomposition (see description below).

b. Explore the method of *polygonal variation*, the term we have given to a series of sound realizations. Roughly, this is a stey-by-step construction of a pressure curve that is modified at each step (period) by a stochastic device, modified in the sense of time and also in the sense of the pressure values at each sample. Acoustical experiments using a computer and a digital-to-analog converter have shown that, for special values of the mathematical device, there arises a sort of probabilistic resonance that engenders rhythmic mulitiplicities of timbres, dynamics, attacks, and macroforms. The principal distributions used until now are the logistic and Cauchy distributions. (See App A.)

c. Explore a sort of "palindromization" with stochastically variable amplitudes, of the *polygonal variation* that makes possible a modulation of the preceding macroform at a higher level.

d. Explore clonings (in the etymological sense, arborescences) of polygonal variation; given a polygonal variation, a point stochastically chosen becomes a germ that engenders a new branch (a new *polygonal variation*) for which the characteristics are defined stochastically. This process may be applied to several trunks at the same time. (For realizations for instrumental music, see Appendix: B.)

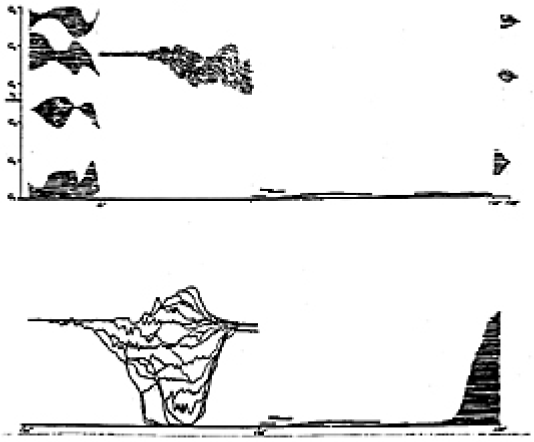
e. Explore Markovian processes on several interlocked levels. For example, we can consider clouds (configurations) of points, such as the Gabor grains (*Formalized Music*, p. 54) or grains that have been designed on the UPIC, and link them with the help of transition probability matrices in the discrete case or with the z transform in the continuous case. We may then consider these linkings, in turn, as states and link these states by a Markovian process distinct in general from the preceding one. Therefore we need to explore chains that are nested, one inside the other. (See Appendix B.)

f. Explore Cartesian products of sets of points taken from the spaces of sound characteristics, using the structures of finite and infinite groups. Example: take a subset of clouds (configurations) of points (notes) or of designs made on the UPIC and consider the Cartesian product of these points with the points taken from a three-dimensional space (e.g., intensity, duration, density), but taking as a model the hexahedral group of the cube (subset of couples of Cartesian products provided with symmetries of transformations distinctive to the cube). This would occur in the outside-time domain. (By "outside time" I mean the domain in which time plays no role whatsoever. For example, the pitch intervals of the white piano keys form a structure that is in the outside-time domain. On the other hand, a melodic pattern based on the piano keys lies in the time domain, because their temporal order matters.) Other examples on a higher level of complexity are the structures of *Nomos Alpha* and *Nomos Gamma*, described in *Formalized Music*. For the inside-time domain, we will use the relations of the hexahedral group by following its structure, given by the cubic group table. (See Appendix B.)

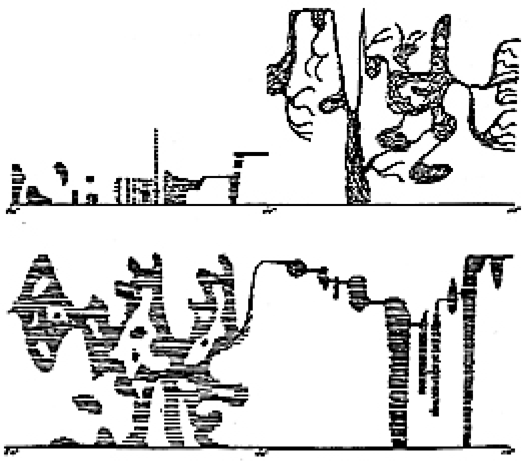
g. Explore *sieve theory*, which generalizes the notion of the scale to all ordered sets, such as time instants, durations, intensities, densities, degrees of order, and so on, and inject this theory into the preceding areas of research in the first stage, then inject it into itself and/or use it independently. (See Appendix B.)

h. Explore logical functions applied to sets of sound characteristics or to sets of already structured sets. (See Appendix B: *Herma*, etc.)

i. Explore the generation of lines in any two-, three-, or n-dimensional sound space by defining each point as a function of probability functions (Random walk, Brownian movement [*Formalized Music*, p. 246]). (See Appendix B.).



Iannis Xenakis: MYCENAE-ALPHA, page 1



Iannis Xenakis: MYCENAE-ALPHA, page 2

Iannis Xenakis: MYCENAE-ALPHA, page 3

Microcomposition

Besides work on the UPIC, we are exploring the region of algebraic microcomposition according to non-Fourier methods, rather than Fouriertype methods such as Music V, to which most other laboratories limit themselves. This is what distinguishes our work at the CEMAMu. A statement of the problem follows.

Sound Synthesis Outside Fourier Synthesis (Analysis)

The central idea is based on the following two points:

1. A sound may be completely represented by its curve of atmospheric pressure variation in time. It is this curve that strikes our ears and nothing else. Consequently, to judiciously construct pressure-time curves (linear forms) goes back, in theory, to fabricating any desired sound through digital-to-analog conversion. This curve and its corresponding sound (music) will be considered as an *entity*.

2. The principle of repetition and of more or less faithful duplication is general and aids in the comprehension of music at all its levels, from the microscopic to the macrosopic. On the microscopic level, for example, the ear not only detects faithful repetitions in the form of timbre but also takes into account their densities in the form of pitch. On the macroscopic level, canons, variations, and so on are equally immersed in this principle of renewal. Each event, wherever it occurs, is in a sense unique, separable, and not exactly reproducible because of the loss (even when it is almost negligible) in the fidelity of a possible duplication. this could be because of the time that has elapsed between two reproductions. But with a sufficient "approximation", they can "appear" identical (within the zone of approximation), *forming equivalence classes* in which the individuals are separable in general while merging in particular cases. The absence of repetition in the pressure-time curve is heard as noise, therefore as an extreme entity.

The dialectic union of these two basic points may be accomplished in three ways:

1. Starting from harmonic synthesis–that is, the strict periodicity of an elementary trigonometric form [sin(omega t)] produced by uniform circular movement and of its appropriate superpositions (Fourier)–one can construct, in theory, any more or less periodic waveform in the pressure-time space.

2. Starting from a deliberately non-periodic waveform(Brownian movement) in the pressure-time space, one may proceed to inject periodicities. -that is, duplications–either of fragments of the original wave or of sections set up separately, leading to a curve that is more or less periodic. We can see clearly the symmetry of these first two processes.

3. Starting from a pressure-time curve defined by some given function, be it probabilistic, algebraic, or trigonometric, one may continue by repeating this curve and at the same time injecting a stochastic modification into it after every repetition. This stochastic modification is chosen so as to produce the statistically continuous negation of the original period, affecting the timbre, pitch, rhythm, intensity, and general evolution simultaneously. Now, in general, for any entity, let us suppose that the reproduction strays more and more from the entity of origin–in other words, that the deviation is applied at the same time to all parts of the entity. The entity will be pulverized into a statistical cloud of constituent elements. On the macroscopic level, we will have an amorphous cloud of sounds, rhythms, timbres, and dynamics; on the microscopic level we will obtain a Brownian curve that will be perceived as white noise. So we are introducing here the stochastic element as the limit of periodicity in the broad sense–in other words, renewal of the entity and at the same time a greater and greater negation in the reproductions.

At each reproduction of any entity, the entropy of the entity increases according to a certain *delta*–that is, the information describing the entity degrades partially at each renewal, irretrievably. It becomes the job of the composer to master, with intuition and reason at the same time, the doses of these entropydeltas circulating through all the macro-microintermediate levels of the musical composition. In other words, one establishes an entire range between two poles–*determinism*, which corresponds to strict periodicity, and *indeterminism*, which corresponds to constant renewal–that is, periodicity in the large sense. This is the true keyboard of musical composition. Thus we emerge in a domain of multiple scientific and philosophic resonances. The continuity and discontinuity of the mathematicians and of the time-space of quantum physicists are such resonances.

The question that arises in all its generality is to know which mathematical construction to specify to the computer so that what is heard will be as interesting as possible–new and original. Without dwelling too long on this, I will cite an interesting example belonging to a case I was able to discover sometime ago by using the *logistic* probability distribution. For certain values of its parameters a and b and its elastic barriers, this distribution goes through a sort of stochastic resonance, through a most interesting statistical stability within the sound produced. In fact it is not a sound that is produced, but a whole music in macroscopic form. This form is the result of rhythmic transformations, giving a polyrhythm of events with variable timbre, changing pitches and intensities–in short, rhythmic strands of meeting and jostling sounds. I have used this procedure in the music of the DIATOPE at the Centre Pompidou.

To show to what extent this duality (that is, the entity and negation of the entity by varied reproductions at each step) is important, I put forward again and more explicitly the following question in the specific case of sound synthesis by computer and digital-to-analog converter: how can one obtain a rich, living, previously unheard-of sound? Does one start from an entity and its reproductions and inject probabilistic variations, creating greater and greater deviations from the initial entity, which tend toward a stronger negation? Or, on the contrary, should one start from an absolute negation–in other words a Brownian curve containing absolutely no germ whatsoever of an entity–and inject more or less varied reproductions of fragments of this curve, so as to engender progressively or explosively, an unheard-of, rich, living sound? In the first case, one would define the entity by strict periodic functions (trigonometric, for example) stacked or adroitly combined, then inject probabilistic perturbations at each reproduction of the entity. For the second case, one would define a set of functions of probability functions describing a specific Brownian movement that would constitute a furthermost negation. Then one would inject reproduction laws for connected or unconnected fragments of the Brownian curve to define the entity corresponding to these laws. These are two pathways, opposite and symmetrical, to rich, living, unheard-of sound. Naturally there is no exclusivity of one pathway over the other, and the results can be extremely interesting and strikingly different in the two paths.

Here is another expression of this universal duality, this time in philosophy, formed by the entity and its negation: the duality of the conflict opposing the thesis of Parmenides to that of Heraclitus. Parmenides decided that Being must exist always and everywhere, homogeneous without variation. Heraclitus decides that nothing is immutable, that everything changes. Thus expressed, these two positions are not compatible. They become compatible, however, if one decides that the Being of Parmenides is the entity that we invoke at the beginning. But it is an entity that would not last–as if time were formed of strings of cells and the entity inscribed in this bounded set of cells would not be able to avoid disapperance and death, once all the limits were reached in exchange for an imperfect reproduction. Then the perpetual change of Heraclitus is precisely realized by the reproduction of this entity in a chain of renewals–that is, in periodicity in the large sense. Thus, in this way, the Being of Parmenides conserves its integrity in the entity but is stained with temporal, spatial, and homegeneity limitations. Change, in general, cannot be instantaneous and total but is obtained progressively by a periodicity that is synonymous with varied reproduction, although it can be explosive at times. The universe of genetics is a beautiful and clear incarnation of this marriage between Parmenides and Heraclitus. Music is another.

Composing with light

Composing with sounds for the ear leads us to compose with light for the eyes. The laser beam and the electronic flash are the equivalents of beautiful sounds. To make them gleam in space is to create music for the eyes–visually abstract music that would put galaxies, stars, and their transformation within the reach of humanity, on a terrestrial scale, of course. This music for the eyes is created with concepts and procedures stemming from musical composition. The result is a new art of vision and hearing that is neither ballet nor opera, but really an abstract spectacle in the sense of music, of the astral or terrestrial type. Movements of galaxies, (sped up) storms, and aurora borealis are examples of what this new art not just recreates–this would be without interest–but truly creates with the means put at its disposal by the present technology. Presently a new type of artist can master events of the size of a large city if given the means. And soon the artist will be able to go out into the cosmos. This is realized with and in the *DIATOPE*. I conceived and designed the *DIATOPE* in its plastic-fabric tent (a special architecture in hyperbolic paraboloids) for the inauguration of the Centre Georges Pompidou in Paris. Being itinerant, it could represent the Centre Pompidou in other cities in France or other countries. After Paris, it went in 1979 to Bonn, West Germany, where it was invited by the mayor of the city.

In the *DIATOPE*, four laser beams (4 watts each) are equipped with optical devices that produce varied light effects. With these laser beams, 400 special mirrors create multiplicities of luminous spider webs in movement. Moving pools of light or sprays of luminous arrows trace in the space and on the black fabric of the tent trajectories of shooting stars or mosaics of bursts of light. Swirling configurations surround the spectator seated or lying on a glass-tile floor that lets through other events underneath. In addition, 1600 electronic flashes form revolving spirals, forms invading or disappearing in total blackness. These flashes are mounted on a metallic net suspended under the plastic shell. The music, recorded on seven tracks, is distributed automatically by the machine-program score, in continuous movements, to the 11 high-quality loudspeakers. The commands come from a nine-track digital tape drive that decodes an *image* of the set of simultaneous commands (around 2000), each twenty-fifth of a second. The commands are dispatched by cable to their destination in the space. The 46-minute spectacle consumes 140,500,000 binary commands. Naturally, to control and coordinate all these configurations, their transformations, and their movements, it is necessary to use the computer either interactively or by writing a digital tape according to a special light-machine program score. This digital type, decoded every twenty-fifth of a second, commands the states of thousands of light sources or optical devices of the visual music. The light composition and the digital type were realized at the CEMAMu; the music was realized at the CEMAMu and then completed at the electronic studio of the Westdeutscher Rundfunk (WDR) in Cologne, West Germany.

UPIC

To think up music as composer, craftsman, and creator, it is first necessary to study solfège, notation, music theory, and even an instrument over a long time. And since, in addition, musical creation is considered superfluous, very few people are able to attain it. Thus the individual and the society are deprived of the formidable power of free imagination that musical composition offers them. We are able to tear down this iron curtain, thanks to the technology of computers and their peripherals. The system that has succeeded at this 'tour de force' is the UPIC (Unité Polyagogique Informatique du CEMAMu). The principle is the following: on a special drawing board one traces designs with an electromagnetic ballpoint pen. These designs are read by the minicomputer to which the table is connected. The designs are interpreted, according to the choice of the user, as pressure curves, dynamic envelopes, scores in the time-pitch domain, and so on. The computer calculates graphic command data, and the result, after being sent through a digital-to-analog converter, is heard immediately on the loudspeaker and recorded on a tape recorder or a digital tape drive. In this way one may create banks of waveforms, envelopes, and graphic scores. One may mix, delete, and realize many of the operations of a traditional electronic music studio by doing nothing more than pointing with the electromagnetic pen to various parts of the table that are sensitized like keys or buttons of an ordinary electronic device. Children may draw a fish or a house and listen to what they have made and correct it. They can learn, progressively through designing, to *think* musical composition without being tormented by solfège or by incomplete mastery of a musical instrument. But as they are led to construct rhythms, scales, and more complex things, they are also forced to combine arithmetic and geometric forms: music. From whence comes an interdisciplinary pedagogy through playing. All this is naturally valid for the "man on the street" and a fortiori for the researcher and the professional composer, since the sound is calculated in very thin slices of thickness of 1/50 000 of a second.

Conclusions

What emerges from all this is that for music and the visual arts of tomorrow it will be necessary to educate artists in several disciplines at the same time, such as mathematics, acoustics, physics, computer science, electronics, and the theoretical history of music or the visual arts. They will need fundamental knowledge of a theory of forms and of their transformations, whether in paleontology, genetics, or astrophysics. It is important to encourage them and to give them the means to create with a system such as UPIC for musicians and an analogous one for visual artists.

But the touchstone of this evolution will be in the training of a large number of masses, as artist-creators right from the start of kindergarten all the way through the present national education in the same way as the massive training in the scientific disciplines in the high schools. To this end *telematics* will have a strong influence by making possible for the first time immediate creation at home through display terminals. It will enable distribution and public communication with feedback of individual realizations with the aid of a system like the UPIC at home. A device like the UPIC will soon become inexpensive enough to be purchased by anyone.

Postscript: Some parts of this article were taken from a text that appears in the book *The Art of Music: Tradition and Change* by William B. Christ and Richard P. Delone of the School of Music, Indiana University, Bloomington, and are used here with their kind permission.

[1] UPIC stands for Unité Polygogique Informatique du CEMAMu. UPIC is a graphics-based computer sound-system at the Center d'Etudes de Mathématique et Automatique Musicales (CEMAMu) in Paris.

Appendix A: Correspondence between certain developments in music and mathematics

MUSIC

500 B.C.

Pitches and lengths of strings are related. Here music gives a marvelous thrust to number theory and geometry. Music invents the incomplete scales.

No correspondence in music.

300 B.C.

Invention of the ascending, descending, and null intervals of pitches, in the additive language introduced by Aristoxenos, who also invents, in theory, a complete, equally tempered chromatic scale with the twelfth of a tone as the modulus (step). In parallel therewith there is a continuation of work with the multiplicative (geometric) language of the string lengths, which in fact is a translation of the additive pitch language (Euclid). Thus, music theory highlights the discovery of the isomorphism between the logarithms (musical intervals) and exponentials (string lengths) more than 15 centuries before their discovery in mathematics; also a premonition of group theory is suggested by Aristoxenos.

1000 A.D.

Invention of the two-dimensional spatial representation of pitches linked with time by means of staves and points (represented by Guido d'Arezzo), that is three centuries before the coordinates of Oresme and seven centuries (1635-37) before the magnificent analytical geometry of Fermat and Descartes.

1500

No response or development of the preceding concepts.

1600

No equivalence, no reaction.

1700 and 1800

Rediscovery, through practice, of the well-tempered chromatic scale (acme with Johann Sebastian Bach). Music is now left behind in the field of basic structures. But, on the contrary, tonal structures, polyphony, and the invention of macroforms (fugue, sonata) are advanced and bring to light the seeds that most certainly will inoculate a new life in the music of today and tomorrow. The fugue, for example, is an abstract automaton used two centuries before the birth of the science of automata. Also, there is an unconscious manipulation of finite groups (Klein group) in the four variations of a melodic line used in counterpoint.

1900

Liberation from the tonal yoke. First acceptance of the neutrality of chromatic totality (Loquin [1895], Hauer, Schoenberg).

1920

First radical formalization of macrostructures through the serial system of Schoenberg.

1930

Reintroduction of finer pitch gradations through the use of quarter tones, sixth tones, etc., although still immersed in the tonal system. (Vyschnegradsky, Haba, Carillo).

1950

Second radical formalization of macrostructures with permutations, pitch modes of limited transpositions, and non-retrogradable rhythms (Messiaen).

1953

Introduction of the continuous scale of pitches and time (use of real numbers) in calculating the characteristics of sound, even if, for reasons of perception and interpretation, the real numbers are approximated with rationals. (This is my own contribution, theoretical as well as musical, which included as well the use of various domains of mathematics such as probabilities, logic calculus, and several structures including group structure. These will play an important role later in macro- and microcomposition).

1957

New formalizations in music on the macrostructure level: stochastic Processes, Markov chains, though used in quite different ways (Hiller, Xenakis), and also the use of computers (Hiller).

1960

Axiomatics of the musical scales with the sieve theory and introduction of complex numbers in composition (this is also a result of my work).

1970

New proposals in the microstructure sounds by the introduction of continuous discontinuity with the aid of probability laws (random walk, Brownian movement). This continuous discontinuity is extended to macrostructures, thus introducing another architectural aspect on a macrolevel–for example, in instrumental music (this also is a result of my work).

MATHEMATICS

500 B.C.

Discovery of the fundamental importance of natural numbers and the invention of positive rational numbers (fractions).

Positive irrational numbers–e.g., square root of 2 (Pythagorean theorem).

300 B.C.

No reaction in mathematics. Number theory is left behind in respect to music theory and its practice, and it lies dormant in the west during more than 15 centuries in spite of the concept of infiniteness and of differential and integral calculus, first felt by Archimedes.

1000 A.D.

No parallel in mathematics.

1500

Zero and negative numbers are adopted, Construction of the set of rationals.

1600

The sets of real numbers and of logarithms are invented.

Number theory is ahead of but has no equivalent yet in temporal structures. These structures will come later with stochastic processes, game theory, automata, etc. Invention of the field of complex numbers (Euler, Gauss), quaternions (Hamilton), the definition of continuity (Cauchy), and the invention of group structures (Galois, Abel).

1900

The infinite and transfinite numbers (Cantor). Peano axiomatics of the natural numbers. The beautiful measure theory (Lebesque, Borel, Heine).

1920

No new development of the number theory. A discussion of some older contradictions in set theory. (Music will catch up in the coming years.)

Appendix B: Mosaic compositions by Iannis Xenakis

ST Group Logical Operations on Classes

ST/4-2 Akrata Herma

ST/10-080262 Nomos Alpha Eonta

ST/48 Nomos Gamma

Morsima-Amorsima

Atrées

Strategie

Polytope de Cluny

(sound synthesis: ST + Cos-G Gaborsignal)

Sieves RandomWalks Arborescences

Persephassa Mikka Evryali

Nomos Alpha Mikka-S Erikhthon

Nomos Gamma Cendrées Cendrées

Mists N'Shima Empreintes

Nekuia Noomena

Ais Phlegra

Khoäi

Polygonal Variations Markov Chains UPIC

Legend d'Eer Syrmos Mycenae-Alpha

Jonchaies Analogiques A & B Anemoessa

Ikhoor

Spectacles of Light and Music

Polytope of Cluny: first fully automated spectacle of light DIATOPE: fully automated spectacle of light and music, making use of all the other means of composition on the macro-micro and intermediate levels.

These two spectacles intertwined with other spectacles such as the Polytopes of Montreal, Persepolis, and Mycenae.