Micropolyphony

Motivations and Justifications Behind a Concept Introduced by György Ligeti

A Partial Analysis of *“Atmosphéres”*
by
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Abstract

This essay investigates the idea of *micropolyphony* introduced by György Ligeti and analyzes a section (bars: 44-53) of *Atmosphères* for Large Orchestra (1961).

The usage of a high number of distinct individual parts in such a way that their individual motions can not be distinguished anymore but an overall dense and composite structure is then heard instead is the most basic definition of micropolyphony.

Micropolyphony is used in many of Ligeti's works[1] but it's most extended application can be seen in *Atmosphères* for Large Orchestra (1961); specially at bars: 23-29 and 44-53. The section extending form bar 44 to 53 will be the main subject of this study[2].

This section is examined from the points of view of orchestral performance issues, conductor and instrumentalists, possible alternate score-writing options[3].

The resulting musical texture's spectral and sonogram images as well as the resulting chord-cluster formations, interval and rhythmical structures of the section and their evolutions will be also scrutinized.

Polyphony and perception, the saturation of the aural perception are examined.

The micropolyphony's roots are sought after in Ligeti's and other composers work in the electronic music research laboratories.

The process's expansion in today's *Granular Sound Synthesis* and other spectral sound creation and manipulation techniques are shortly investigated.

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[1] *Requiem, Apparitions, Lux Æterna*, (parts of) String Quartett N.2 and many others

[2] Rehearsal letters $\boxed{\text{H}}$ to $\boxed{\text{J}}$

[3] Aleatoric or partly aleatoric notations

Chapter 1

Polyphony

1.1 Polyphony and Perception

It is often stated by human physiology researchers that a human brain can only accurately follow two simultaneous independent musical voices (parts).

That means every piece of music with more than a two parts polyphony will be somewhat reduced in our perception to a two part structure by merging some voices together. Parts bearing the closest semblance to each other will be merged into one to form a two-note homophonic structure which then can be easily followed.

1.2 Two-Voice Polyphonies

In the works of the most polyphonically oriented composers, as in the *Stile Antiqua* period or with Johann Sebastian Bach, one can see an intuitive application of the natural human polyphonic perception limits.

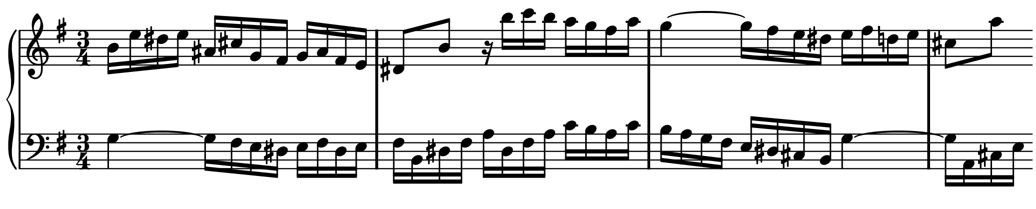

Figure 1.1: Example of independent two-voice writing: J. S. Bach, *Das Wohltemperierte Klavier* Vol.1, Fugue N.10 BWV855

Bach, in his few two-voice fugues seems to literally unleash each of the two-parts but even in his three-voice polyphonic writings he often “links” two of the parts in an homophonic evolution.

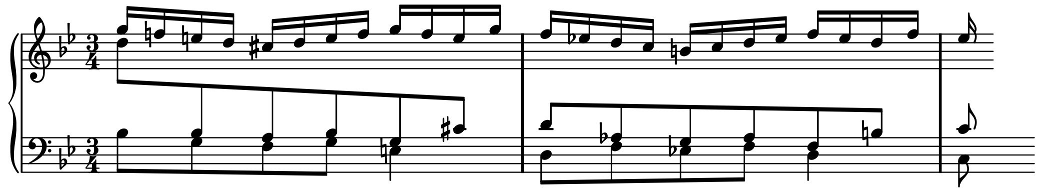

Figure 1.2: Example of linked voices in a three-voice, fast tempo, instrumental fugue: J. S. Bach, *Das Wohltemperierte Klavier* Vol.1, Fugue N.21 BWV866

Similar textures also show frequently in instrument-unspecified fugues[1].

1.3 More Voices

Bach’s four and five-part contrapuntal writings indicate a clear inclination to group voices into harmonic blocks.

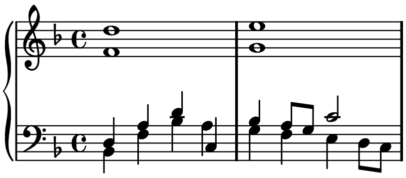

Figure 1.3: Example of linked voices in a four-voice, slow tempo, instrument-non-specified fugue: J. S. Bach, *Die Kunst Der Fugue, Contrapunctus XIX* BWV 1080

Through music history, when music turned to a more “vertically oriented” homophonic style composers kept considering the human aural perception limits when it came to speed and harmonic density. The faster was the speed and the simpler were the harmonies and the polyphonies.

This was the way of the nature and there were no recording technology to experiment on those limits. Actually there is no evidence that the question of human perception limits ever arose.

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[1] Example: *Die Kunst Der Fugue*

1.4 Chopin's Atonal Movement

One striking example of mid-nineteenth century is the last movement of Chopin's Piano Sonata N.2 in B-flat Minor Op.28.

Ligeti calls this piece "…probably the first atonal piece of in the history of music"[1]

Although there is a clear harmonic structure which appears in the *quasi-arpeggio* evolution of the identical lines of both hands, the speed of harmonic changes and their intently chromatic profiles actually makes the "feeling" of tonality to weaken to a considerable degree.

The perception of such a music is more "global" rather than detailed (structural). The popular epithet "winds blowing through graves…" actually gives a rather poetic yet accurate description of how this music was (is) perceived.

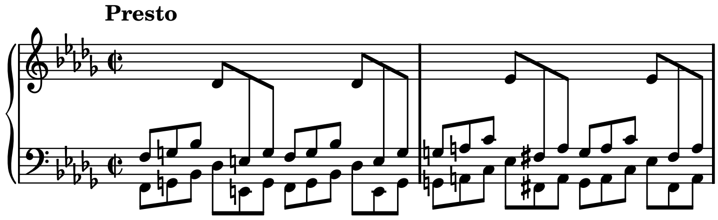

Figure 1.4: According to Ligeti music history's first atonal piece: F. Chopin Sonata N.2 in B-flat Minor, Fourth Movement "Presto"

Beside being called "the first atonal piece" by Ligeti, the Chopin example above brings us to the very important question of sheer musical speed and perception.

1.5 How Fast Can We Play and Hear?

According to physiological research we can clearly distinguish individual sonic events up to twenty events per second, which is a 50 millisecond duration for each sound (event).

It is interesting to note that this lower level for distinct perception matches our physical performing ability on a musical instrument and it is analogous and quantitatively very close to the well-known *persistence of the vision* phenomenon.

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[1] *Pensées Rhapsodiques* First published by the Fondazione Internazionale Balzan [1]

The seeing of a continuous action in cinematography is possible at a rate of at least 20 images per second. The industry standard in motion picture is 24 images per second. Going down from that speed we start to see first a blurred and jerked motion and, down again, we start to distinguish each actual frame.

Although it is closely related to instrumental specifics, note intervals, hand positions and so on, a speed of twenty notes per second is not only our playing speed-limit but also our limit for distinguishing individual musical events. Faster than this, the events blur in a *glissando* texture. This particularity is often used in trills and *glissandi*.

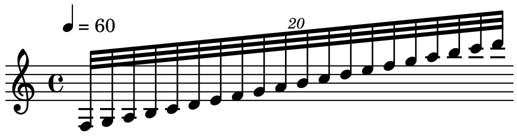

Figure 1.5: According to recent research the fastest notes we can distinguish as individual elements

In the piano literature, some examples stretching the limits for the fastest playing possible are worth mentioning here.

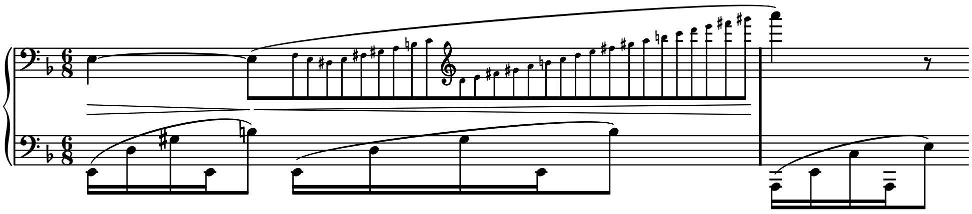

Figure 1.6: F. Chopin Prelude N.24 in D Minor. One of the fastest scales a pianist has to play…

In the Chopin example, the piece is often performed at a tempo of around one second (60 BPM) for a dotted quarter note. If the ascending scale starts, as it should be, at the last eight note of the first beat we have 24 notes to play at the second beat which lasts for one second in the usual tempo of this piece.

This is practically impossible. The passage is often performed, even with the most skilled pianists by starting the scale slightly earlier at the end of the first beat and by "holding" a little during the second beat.

Other examples of fastest notes are not even approaching this limit. In

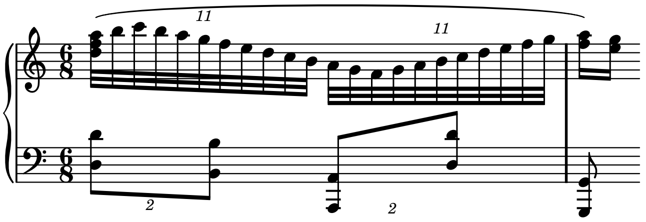

Figure 1.7: I. Stravinsky *Trois Mouvements de Pétrouchka* III. *La Semaine Grasse*

the last movement of the *Petrouchka* suite by Stravinsky we have, at the right hand, eleven notes to be played at approximately one second time, the usual tempo of the passage is 60 BPM. This requested speed is almost identical to another passage, for the left hand, in the first movement of the same piece.

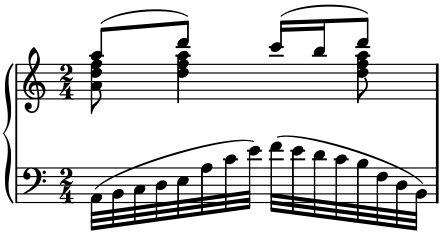

Figure 1.8: I. Stravinsky *Trois Mouvements de Pétrouchka* I. *Danse Russe*

1.6 The Electronic Music Studio of the W.D.R.

Sound manipulations for a new musical expression were made possible by the advent of the magnetic tape. Different sorts of discs and rolls previously used to store sound recordings were not malleable for such creative purposes.

The concepts and the names of “sound objects”[1]and *Musique Concrète*, both created by Pierre Schaeffer and Pierre Henry in Paris at 1948, were given to pre-recorded samples of natural sounds, *Objets Sonores* and to their use for music composition, *Musique Concrète.*

However the creation of a true *synthetic* music took place in Cologne, at 1950 in the entourage of Herbert Heimer.

The main approach was different from the *Musique Concrète.* In this *synthetic music* electronically generated oscillations were first recorded on

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[1] *Objets Sonores*

fragments of magnetic tape which were then manipulated in any possible way. Mixing and changing the playback speed were the most often performed manipulations.

In 1957, Ligeti was assisting Gottfried Michael Koenig in the electronic music studio of the *Westdeutscher Rundfunk* in Cologne for the realization of a piece called *Essay*.

Essay by Koenig was mainly composed of sinusoidal sounds which can be easily followed by the ear at some points but at other moments, those sounds formed interesting conglomerates where none of them could be individually spotted. That was due to the extreme brevity of them and to the high speed of their succession in time.

In *Essay*, the simultaneity of sounds above and below the differentiation level of the ear[1] created an interesting texture.

In this texture one could spot and follow those sounds above the perception threshold, sounds longer than 50ms., as a kind of "melody". At the same time, sounds below that threshold, shorter than 50ms., are perceived as if they were "simultaneous" with the others. Even when they were not. That "false simultaneity" not only created an interestingly complex sound aggregate, but another quality, previously unheard of, emerged as well.

Koenig called this quality the "sound (timbre-color) of movement" *Bewegungsfarbe* [1]. Rhythm is not anymore perceived as a motion but instead rather a constantly changing sound-color is heard.

More layers of this composite "sound-color" could be created by varying the dynamics of the component waves.

Seen from today, it seems that Koenig and Ligeti have "discovered" the principle of *Granular Sound Synthesis*[2].

In Granular Synthesis extremely brief sounds, when agglomerated create a layer of a complex timbre.

Each of the "grains" can be varied in pitch, intensity and overtone components[3] while the overall pitch and intensity of the whole complex can also be made continuously changing.

Today, *Granular Synthesis* is widely used tool. Various computer software exists and it has various implementations in the *Csound* electronic music software[4]

In an article formerly published in a compilation named *Rückblick in die Zukunft*[5], republished in[1], Ligeti describes the basic method of working in

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[1] Longer or shorter than 50 ms.

[2] See Granular Synthesis, Appendices page:35 for more information

[3] harmonic composition in the acoustical sense

[4] See Csound, Appendices page:38 for more information.

[5] Severin und Siedler, Berlin, 1981

the Cologne studio:

> [. . .] a sinusoidal current generator creates sine-waves at a controlled frequency. Those waves are recorded, separately, on magnetic tape. Complex waves can be obtained by mixing those sine-waves. Following a pre-defined compositional plan, the tape is cut into pieces and re-assembled to form the desired succession of sinusoidal and complex sounds. Then those sounds are played simultaneously on two tape recorders and the mix is recorded on the third tape-deck. During the copying process the volumes of the sources can be freely altered. The resulting tape is then cut and the fragments are assembled again and mixed with others.
>
> The process can be repeated *ad infinitum* but the building up of the background noise during the re-mixing process limits its practical use to two or three "generations" at the maximum.

1.7 "Fake" Polyphony

Before getting into "microscopic" polyphony, the main subject of this essay, another series of experiments made by Ligeti at the Cologne studio worth mentioning.

We previously stated that by varying the dynamic levels of the layers sinus signals mixes different "melodies" could be heard. This is because our perception was creating connections between signals of different levels[1].

Ligeti also noted that the difference between the perceived intensity of a signal and its scientifically measured volume is releated to the signal's harmonic[2] complexity. Complex (i.e. "musical") signals, when they are at the same volume than sinus waves are heard as if they were stronger.

That difference in hearing makes it possible to create a kind of "layered" polyphony which Ligeti describes as:[1]

> By using different intensity levels for each note and each sound, and by integrating sounds which are harmonic, subharmonic and non-harmonic in between a succession of sinus waves, it is possible to create a "fake" polyphony inside a monophony. This is possible because of the mental connexions at higher levels that we can create between different kinds of sounds.

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[1] See: Figure:1.9, page:8

[2] overtone

If the higher level signals are not too dense we perceive, inside the true single voice, a complex of several voices. By creating a more detailed sequence we reach a saturation point where the shape of the super-signals[1] start to blur, too many layers neutralise each other and the phenomenon of "fake" polyphony is gradually lost.

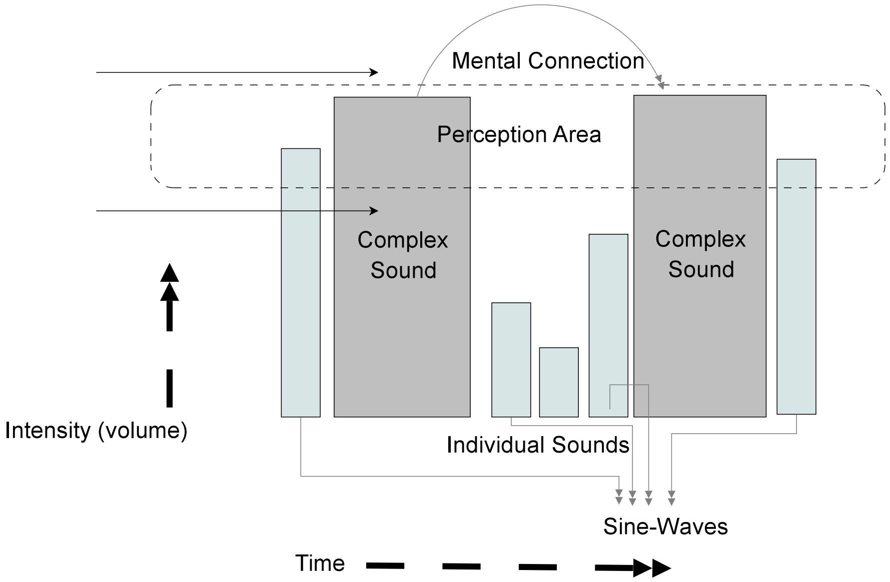

Figure 1.9: Schematic representation of the perception of musical events as Koenig and Ligeti experimented on them at the Cologne studio

Ligeti made various experiments at the Cologne studio exploring the "blurring" of musical textures. He tried many *collages* of sounds by getting above and below the perception level.

In 1957, after having experimented with a piece called *Glissandi* to which he relates as an "exercice to learn the studio techniques", he elaborated another piece named afterward *Pièce électronique N.3*.

It is interesting to note that this piece was formerly called *Atmosphères* but in 1961, when Ligeti started a piece for large orchestra, he used that title for the orchestra piece and re-named the electronic piece *Pièce électronique N.3*[1]

The work on the orchestral *Atmosphères* was previously interrupted for the profit of another electronic piece called *Artikulation* which thereafter became *Pièce électronique N.2*.

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[1] Complex sounds

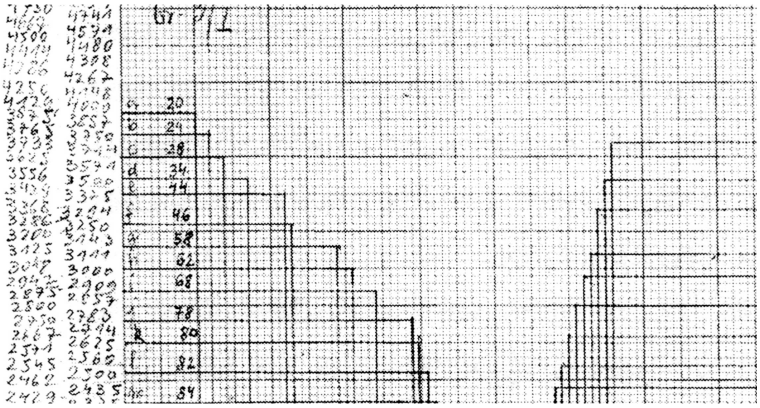

Figure 1.10: *Pièce électronique N.3.* Fragment of the "score".

The "score" for this *Pièce électronique N.3* is drawn, as it was customary at that time for electronic pieces, by using a squared millimetric paper. The vertical axis represents the frequencies, the horizontal lines represent the length of magnetic tape fragments in centimeters. Vertical lines are the connecting points for the assembly.

The "score" is actually a *matrix view*[1] of the music.

While the majority of the sounds used are sinus waves, some electronically filtered noises also appear. Those noises were filtered using a very narrow band filter and they are actually very close to sinus waves but, as described by the composer, they are made "slightly blurred by an halo of external frequencies".

The textures created are almost never static but always moving, evolving and transforming.

The frequencies are hardly legible in the reproduced score[2] which is shrank here to fit the page but it is interesting to note that frequencies were selected in order to produce various spectrums of harmonic and non-harmonic structures.

For harmonic structures, frequencies with plain integer ratios between them are used, higher harmonics are privileged in this piece. Those harmonic and non-harmonic spectræ create a resulting "sound" which is not "created" as the others but can only be heard at the actual audition of the piece. This is a "resultant" harmonic sound.

In autumn 1957, the "score" for frequencies were established and in November Ligeti started the realization of the piece in the Cologne studio.

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[1] Term used in computer "sequencer" software together with the name "piano roll view" to show and edit each note in a pitch-time display

[2] Figure: 1.10

He was first creating the sine waves at the preset frequencies without dealing with the intensities. But, soon the technology of the time made it impossible to continue.

The synchronizing of more than forty layers of sound was a practical impossibility with the technology of the fifties. The out-of-sync shifting created audible differences in the resulting textures which were deemed unacceptable by the composer.

After having completed the work on another electronic piece: *Artikulation* in 1958, Ligeti resumed working on *Pièce N.3* .

This time he confronted with another difficulty: the scoring of the intensities were unrealizable because that necessitated working in three-dimensions... On the surface of the quadrilled paper, pitches were assigned to the vertical axis and time (durations) to the horizontal one.

So he started to notate the intensities on another sheet in close connexion with the frequency-time graph. But he stopped working altogether on that music and also abandoned completely the electro-acoustic realm. The practical impossibilities of composing music exactly as he wanted to do combined with the technical limitations of the equipment made him leave the electro-acoustic music studios forever.

He relates his leaving the studio in the article mentioned before[1]

> As other tentatives for the realization of the piece revealed to be unsatisfactory as well, I promptly abandoned working on it and from summer 1958 I totally concentrated on the composition of pieces for orchestra.

1.8 Closing Thoughts on Ligeti's Experiences in the Electronic Music Studio

It is clearly seen from the above that Ligeti left the electronic music studio because he felt the technology of that time was unsatisfactory for his needs.

Those needs were, and have always been, highly structured, precisely elaborated and very demanding. He has been always very foreign to any *aleatoric* processes and seemed not at all attracted by the "happy accident"[1] which was (and is?) an often stumbled upon phenomenon in many composers dealings within the technological world.

Because he wanted to preset all aspects of his music first and then to control all facets of its performance, he has been profoundly discouraged by the technological limitations.

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[1] An unexpected result obtained by "accident" which is then saw as good and useful.

It is interesting to denote that while many of the composers with Ligeti among them, were attracted to the electronic music studios because there were a possibility for them to accurately create their music as exactly as they wanted it to be, without the intervening of the performer to “sonify” it, Ligeti did not accept to remodel his musical conceptions to fit them in the technological realities of that time.

In this aspect, there is a strong connexion between him and Pierre Boulez in their reasons to depart form the electronic music studios.

More specifically, Ligeti, in his *Réflections faites au départ du studio et plus tard*[1] first mentions the impossibility to work with (sound) *envelopes* and *attack transients.*

Having subtle timbre modifications was also a practical impossibility. The sheer quantity of individual single sine-waves which has to be created, recorded on tapes and mixed for making a complex timbre and its modifications in time was simply not feasible at that “pre-computer” time.

He also states another limiting fact which remained with most the electronic music instruments for a very long time. Before the development of *Frequency Modulation* first and spectral manipulation later, the electronically created sound was, in essence, a static one.

Commonly used voltage controlling devices for pitch *(VCO)*, intensity *(VCA)* and timbre *(VCF)* were almost crude and too regular in their periodic oscillations.

Frequency Modulation (FM) technology allowed for the creation of the first electronic timbre which had the capabilities of controlled aperiodic oscillations evolving in a aperiodic manner.

The famous bell sounds of the first commercially available portable synthesizer featuring the FM sound synthesis, Yamaha DX7$^{\mathrm{TM}}$, were world famous for a reason. They were the first synthetic sounds of the kind.

However the wide timbral capabilities Ligeti was after have been extensively and widely available only with the advent of *Physical Modelling*[1], *Granular Synthesis* [2] and all the spectral (re)modeling tools we have today. They only flourished starting from the 90’s.

Ligeti metions the book *The Technology of Computer Music* by Max V. Mathews[3] and the software *Music-V* as forerunners of a new area in electronic music composition.

The *Music-V* system was to give birth to *Csound*[4].

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[1] See: Physical Modelling Synthesis page:36 for more information

[2] See: Granular Synthesis page:35 for more information

[3] Cambridge, London, The M.I.T. Press, 1969

[4] See: Csound page:37 for more information

1.9 Influences of the Electronic Music Procedures on Ligeti's Instrumental Works

In his essay *Musique et Technique*, originally published in a compilation called *Rückblick in die Zukunft*[1] Ligeti relates that when two of his orchestral compositions *Atmosphères* and *Apparitions* were first performed, in 1961 and 1960, several listeners thought there were loudspeakers disseminated in between the performers.

The illusion was caused by the composer using techniques he already worked on in the Electronic Music Studio of Cologne, techniques he successfully adapted to instrumental music.

He calls that specific technique the "timbre of motion".

> [. . .] by getting below the threshold of "fusion"[2] we obtain modifications of the structure of the musical texture and we get instrumental combinations which are sensibly different from those obtained by using the conventional instrumental combination techniques.

In the mentionned article, he first uses the term *micropolyphony*:

> Already from 1950 I was imagining new timbres, a "static" musique, "sound spaces"[3]
>
> In Budapest, 1956, before my electronic music studio experiences I composed a piece called *Viziók* (*Visions*) which later became the first movement of *Apparitions.*
>
> [. . .]
>
> I applied those experiences to orchestral music, in 1959 in a really different way to the second movement of *Apparitions* right after my stay in Cologne. In the first movement the sound spaces were still static and aligned as successive blocks while, in the second movement, for the first time, the destabilization of those blocks appeared as well as textures modifications and the micropolyphony.
>
> [. . .]
>
> The experiences made in the studio of electronic music by using the "melting of succession"[4] and by stacking a great number of

---

[1] Severin und Siedler, Berlin, 1981

[2] Distinctly perceptible sound

[3] The term will then be widely used in its abbreviated form: soundscapes.

[4] *fusion de successivité*

independently elaborated sounds and sound sequences on top of each other, made me imagine a kind of complex polyphony created by musical textures and networks. I called this way of composing *micropolyphony* because the many rhythmical elements were getting below the threshold of fusion in the polyphonic texture.

The texture gets so dense that the parts can not be perceptible anymore in their own individuality and we can apprehend the whole only as a “whole”, from a higher perception level.

Chapter 2

Micropolyphony: “Microscopic” Polyphony

2.1 Resultant Texture

Micropolyphony is a well fit name for the technique.

In biology microscopic creatures are life forms having all their own, sometimes fairly complex structures, individual lives and behaviors. They appear to naked eye only as a (questionable) volume of liquid, solid or gas.

Micropolyphony is similarly a mass of a musical texture made of a high number of individual parts which can not be distingished as such.

Actually white noise can be thought as the ultimate micropolyphony for it is made of a great number of random sine waves at random amplitudes and frequencies. Yet it is not “polyphony”, it is *noise*.

That is precisely because of its random nature. Furthermore filtered noise is still *noise* up to the point where the filtering goes deeper on and reduce the mass to only distinct waves which then appear as they (still) are: random waves.

The most important aspect of the Micropolyphony procedure of Ligeti is that it is actually composed in all its aspects, not a random process at all. In this sense it differs considerably from similar procedures used by some composers notably by Iannis Xenakis[1]

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[1] See:Xenakis Sound Clouds and Ligeti’s Micropolyphony 3.3 page:18

2.2 Precursory Attempts

Ligeti mentions an interesting orchestral effect, one from the last periods of Romanticism in music: *Feuerzauber* at the end of the *Walkyrie* by Wagner.

He describes the dazzling effect as:

> [...] the figures in the violin parts are so difficult to play in the requested tempo and exactly as they are written that, inevitably performers do make slight mistakes, most often slight rhythmical inaccuracies. That creates little temporal fluctuations (unsynchronizations) between performers. Those deviations are aperiodic and with an usual fourteen First and fourteen Second violin players each making different "slight" mistakes, a scintillating effect results.
>
> [...]
>
> This effect is not the sum of the notes played by each musician, it is rather a new quality of the global sound space.
>
> [...]
>
> I did understand that timbre quality only after having experimented on the sequences of "over-fast" notes of Koenig in the electronic music studio. If that happens as a by-product in the *Feuerzauber*, then I wanted to compose music where such effect would be used intently.
>
> My aim was not to get random variations in the performance of the music but to willingly create transformations of textures in a network of high density polyphony.

Chapter 3

Organization and Composition of the Sound Material

3.1 Why Compose Each Part Individually?

It is clearly asserted by Ligeti that he wanted to control his “soundscape” in a very precise way.

He wanted it to have the right “light, color, texture” and, maybe more importantly the right “evolution”.

In that aim, every part had to be accurately composed in every detail. The overall sound-space’s range being from the bottom to the top notes of all instruments of a complete orchestra, one may think of it, at first, as a quadrilateral area where the height (*y-axis*) is the pitch and the width (*x-axis*) is the time.

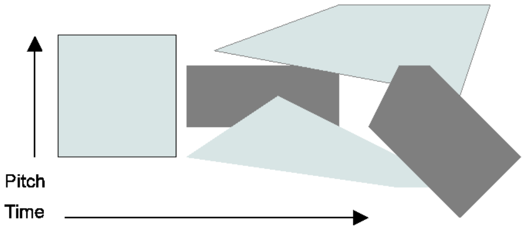

Figure 3.1: Symbolic representation of the usage of the total sound-space

This over-simplistic view, to truly represent the musical thinking of Ligeti, has to be completed by the missing sound-parameters: tone-color (instrumental resources, playing dynamic); event-density; internal animation[1]. Those

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[1] How fast notes in each part move in relation to each other and also in relation to the entire composition

parameters are evolving and can be continuously changing within the shape as well. So there is no real way to represent it graphically.

This aspect of *continual changes and evolution* is what makes the Ligeti soundscapes first and unique in the history.

3.2 Performance Issues

It is (unfortunately) impossible to make first the composition process "easier" for the composer and then the performance process "easier" for the instrumentalists by letting some aspect of the *soundscape* undefined.

It would have been, of course, a lot easier to write only some notes (or note-heads), an overall duration, a more or less general dynamic level and draw a wavy line over the page of the score! That would have been also welcomed by most (all?) instrumentalists...

However in the real world of music performers there are points to consider when using aleatory notes.

Each performer, as a fully trained musician has been playing endless hours of scales, arpeggios and other exercises. Probably doing still so in his professional life. The physical memory is strongly established and when undirected, fingers will unquestionably find, between the notes given by the composer, those successions and assemblages who are closest to the ones practiced before.

Another point is that orchestra musicians are trained to play in sync with their instrumental section or at least with their neighbors.

That reveals the futility of expecting a micropolyphony, or anything closer to it, to emerge by giving musicians more or less directed random notes to play.

Some composers, Lutoslawski being notable among them, have actually used "directed[1] random notes" in parts of their orchestral works. The point is they did not tried to create a soundscape of some duration in this way and the parts playing *partly random notes*, especially in the scorings of such a knowing composer as was Lutoslawski, were limited to a solo or a reduced number of instruments.

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[1] Notes partly defined in pitch rhythm or succession

3.3 Xenakis' Sound Clouds and Ligeti's Micropolyphony Compared

3.3.1 Stochastic Methods

Another way of creating a similar *soundscape* was devised by Iannis Xenakis using his mathematician and architect background.

To create similarly dense structures, Xenakis used *stochastic* processes and formulæ[1].

Stochastic functions are basically conditional random transition tables. The basic rule for them is that an element ε may be followed by another element ω with a probability factor ρ. This is commonly expressed as: $x \Rightarrow y^{\rho}$

Those tables of probabilities are better known as *Markov Chain Processes.*

From	To	Probability
a→	b⇒	.25
d→	c⇒	.30
e→	f⇒	.4
x→	z⇒	.05
a→	f⇒	0

Figure 3.2: Example of a simple Markov chain transitions table. The first line read as: "there is a 0.25 chance (25%) that the element **a** changes to (or will be followed by the) element **b**"

Those elements (or *states*) a, b…can be notes, chords, rhythms or any musical data.

In Figure:3.3, a fragment of the drawing for Bars 52-57[3] of *Pithoprakta* is shown.

Glissandi lines for the strings instruments, previously obtained according to transition tables similar to the one shown above are drawn on millimetric squared paper. The starting and ending times and pitches are set. Those are then transcribed to the music paper.

Those random-based processes as used by Xenakis but also by John Cage[2]are radically different from Ligeti's composition methods.

---

[1] See: Stochastic, Appendices page:40 for more information

[2] Specially in the *Music of Changes*

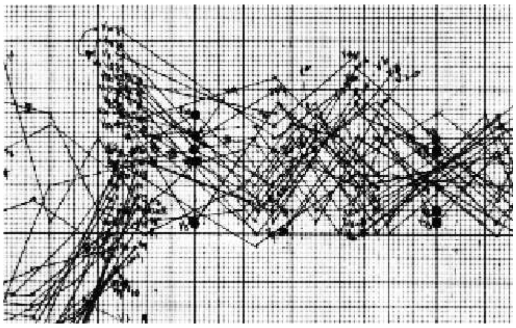

Figure 3.3: I. Xenakis Drawings for the strings *glissandi* in *Pithoprakta*

Figure 3.4: I. Xenakis Score (*Pithoprakta*) form the drawing above.

3.3.2 Ligeti's Method

The most important difference between Xenakis' conditional random processes and Ligeti's micropolyphony lies in the *micro-structural* level.

While random processes as well as deterministic ones deal with the overall density, sound-color and density aspects of the *sound-cloud*, all musical elements: pitch, rhythm, range, timbre and so on are partly (in random processes) or totally (in deterministic processes) under the control of the composer.

However, when each part is considered alone horizontally, *stochastic* processes do not show any kind of micro-structure.

In Ligeti's micropolyphony, by contrast, each part has a structure of its own.

It is striking that every "horizontal slice", as well as every single part, of the music will show a supremely crafted polyphony.

The cello section of the same bars, together with the violas are actually

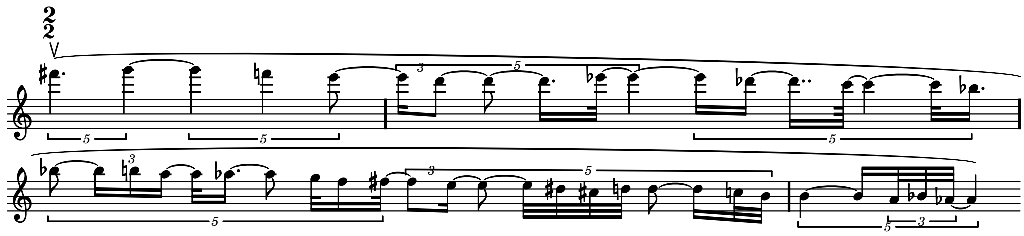

Figure 3.5: G. Ligeti *Atmosphères, Violin I-1, Bar:44. Despite being only one component of the 48-voice polyphony, this line of the number one of the first violins still shows a clear melodic structure.*

playing a mirror canon of the violin parts. When this cello section is examined on its own, it reveals the coherent micro-structure of the polyphony.

Figure 3.6: Cello section, 1 to 10 Bar:44

However one may ask the question “is this audible and if so in what sense?”. It is obivous that the structure shown, one part of the forty-eight voice polyphony, is literallt buried and would never be recognized in the mass of sound.

The point in crafting each part of the micropolyphony to such an extend is to control the shape and evolution of the "soundscape". Individual notes and parts, altough not discernable in their own, are creating the characteristics of the "colour", "shape" and "inner activity" of the soundscape.

Range, rhythm, dynamics and intervals for each part are not meant to be heard as such but rather to be a part of the overall design.

3.4 Microstructures

3.4.1 Intervals

One familiar "Ligeti motif" immediately captures attention. The motif:

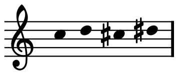

Figure 3.7: Motif widely used by Ligeti in many of his pieces.

This "favorite" motif by Ligeti is the main structural element of his First String Quartett (*Métamorphoses nocturnes* 1953-54). It is the *pc-set* $(0, 1, 2, 3)$, *Forte Code: 4-1*, interval vector: [321000]; a highly versatile set.

Figure 3.8: String Quartett N.1, First Movement, bars:7-8

It is interesting to note that this motif is actually the famous *B.A.C.H.* set.

This motif is the main building block of the whole 48-voice (micro)polyphony. Below are some examples from its occurrences in the beginning of the examined section. Rhythms are removed to show only the pitches.

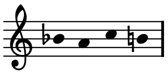

Figure 3.9: Motif *B.A.C.H.* very widely used in the music history

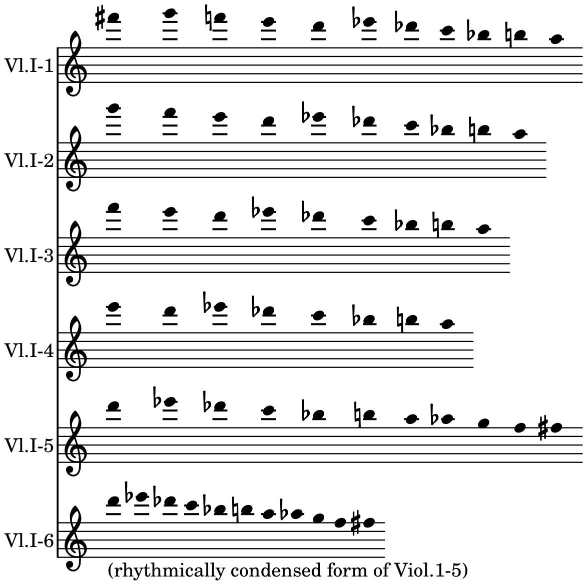

Figure 3.10: *Atmosphères* Sample microstructure. Bars: 44-46 Violins I-1 to I-6

The intervals of the prime form of the set (whole-tone, semi-tone, whole-tone) are used in the form of permutations throughout the section.

It is interesting to note that the whole section (bars: 44-48; up to the re-entrance of the Double Basses at bar: 49, rehearsal letter: I) is composed exclusively with neighbor tones, half and whole.

The few "jumps" which occur at bars 48 *(cello 10 Violin II-14)* or 49 *(Violin I-14)* are clearly for shifting the line back into the range of the instrument. The shift at the second half of the bar 44, Violin II-12-13 and 14 are all marked *imperceptible attack* on the score.

At the beginning of the section; bar: 44-45, violins I and II are moving together in a generally descending motion while violas and cellos are set in an upward motion

The upward motion of the viola and cello parts creates a "rising wave motion" which gradually expands to the violin parts starting from bar 47.

The graph, figure:3.13 (page: 24) shows the overall evolution of the sound-

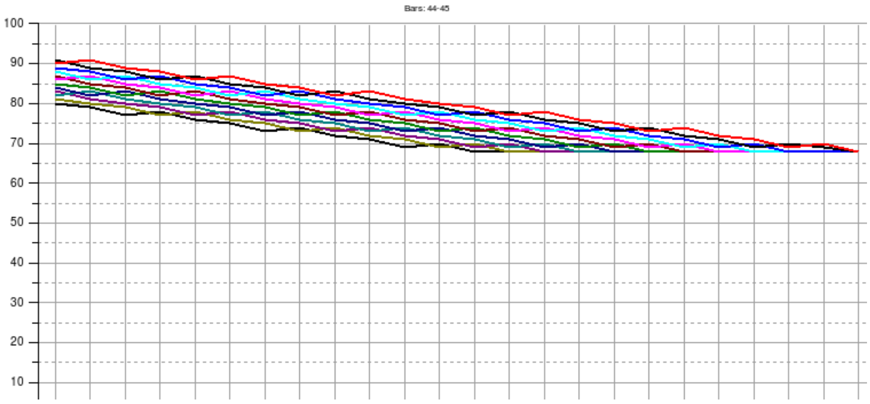

Figure 3.11: Motion of the violins I and II (14 + 14, 28 solo parts). Bars: 44-45. A general descending motion.

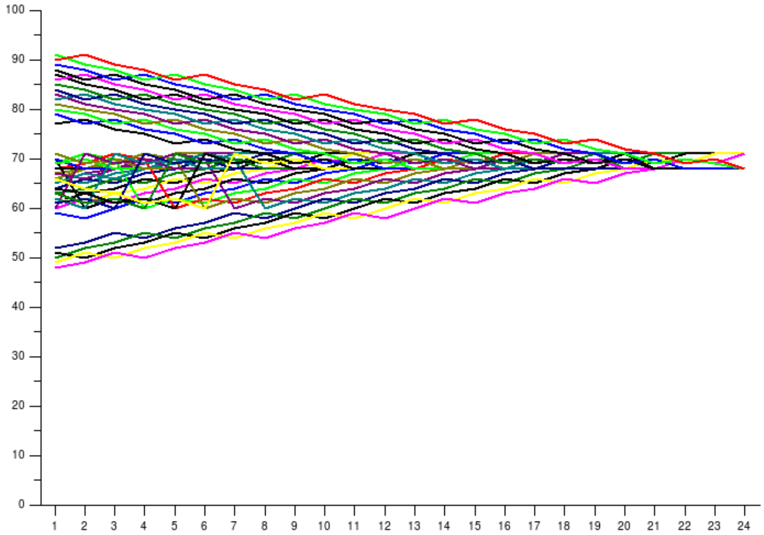

Figure 3.12: Overview of bars 44-45. Strings section all solo 48 parts. Violins I and II are in descending motion while violas and cellos are ascending. At the point where the graph ends the ascending motion of the violas and cellos parts will extend to the violins.

cloud.

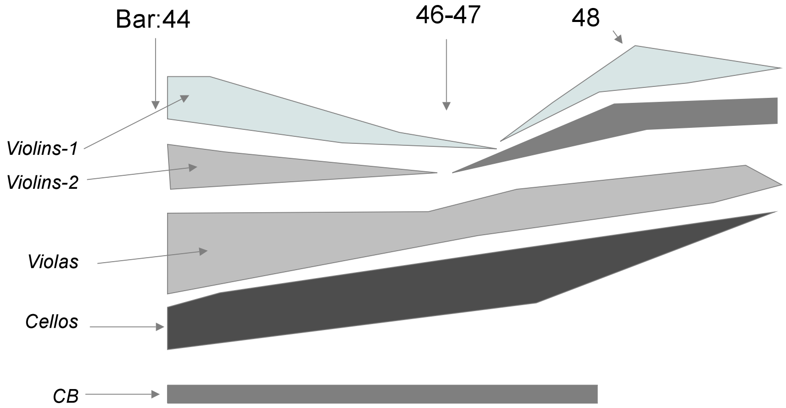

Figure 3.13: A sketch drawing of the evolution from bar 44 to 49. It should be noted that the widening of the boxes is to represent an augmentation in the *density* of the parts

3.4.2 Resultant Clusters and Chords

The section analysed shows a total horizontal *(contrapuntic)* layout, however it is interesting to investigate on the resulting chords and clusters.

Individual part motions are expressly set very fast and asynchronous in rhythms. The music notated in 2/2 time signature at a tempo indicated half-note at 30 BPM so one bar lasts one second. Bars are also divided in two halves by a vertical dotted line to facilitate the reading of the music.

Except for the previous double-basses cluster attack which occurs four bars before (at bar 40) and sustained *tutta la forza, ten.* there is no soft or strong dynamics but everything on the violins, violas and cellos are notated ***pppp*** and even emphasized by an inscription:*imperceptible attack*.

Only the changes at any of the boundaries, the highest and lowest notes for each part will be considered for sketching the resulting clusters.

The notation below reflects the vertical extends and changes in each of the parts in a cluster notation.

The cluster notation shows that all voice motions are neutralizing each other. So the projected *sound-cloud* is a static object on its outlines.

3.4.3 Rhythmical Aspects

Ligeti was one of few composers to be aware of Joseph Schillinger's works. Schillinger (1895-1943)[5] was a composer, music theorist and composition teacher. He endlessly followed the idea of merging sciences and music.

Combining music and mathematics is a long-term dream of many musi-

Figure 3.14: Bars: 44-47. Cluster notation shows that there is only a few significant shiftings in ranges.

cians. From Aristotle to Jean-Philippe Rameau and to Iannis Xenakis, scientifically oriented musicians have sought (and some of them actually found) interesting ways of dealing with musical matters by using their scientific backgrounds.

Schillinger was a very versatile musician. He had some mathematical background and was very found of Jazz music. It is said that the created the first Band in his native Ukraine.

As a technology oriented composer he worked closely with Leon Theremin (1896-1993) and composed music for the *Thereminovox*. He himself invented some interesting musical instruments, with the *Rhythmicon* (1932) among them which can be considered as the first rhythm-machine.

Schillinger settled and worked in the U.S.A. where he was teacher at the Columbia Teachers College and was also giving private lessons, often by mail.

Among his well-known students were George Gershwin, Glenn Miller, Robert Emmett Dolan, Carmine Coppola, Vic Mizzy, Leith Stevens, John Barry and many others.

He has been very influential to music composers working in the motion picture industry in the early forties.

From his rational way of dealing with music theory and composition emerged a *Schillinger System of Musical Composition*[6]. His mailed private lessons were compiled and edited by Lyle Dowling and Arnold Shaw in a monumental book which is published with that title.

His other important work, to which he was referring to "as his most important book" is *The Mathematical Basis of the Arts*[7].

The book has many insights on the process of artistic creation, the history of music and arts.

Few sample citations will enlighten this very important music thinker's approach by doing so it will also help to set Ligeti's attitude and some of his compositional techniques.

Joseph Schillinger wrote in his *The Mathematical Basis of the Arts*[7]

> The history of art may thereupon be described in the following form:
>
> 1. Nature produces physical phenomena, which reveals an aesthetic harmony to us [. . .] This is the *pre-aesthetic*, natural (physical, chemical, biological) period of art creation.
> 2. Man recreates aesthetic realities by reproducing the appearance of the physical realities through his own body, or through a material at his command [. . .] he expresses the laws of mathematical logic through his sensory experience; this is the *intuitive* period of art creation.
> 3. Becoming more and more conscious in the course of his evolution, man begins to create directly from principles [. . .] This is the *rational* and functional period of art creation
>
> [. . .]
>
> It is time to admit that aesthetic theories have failed in the analysis as well as synthesis of art.
>
> [. . .]
>
> The cult of craftsmanship transforms into formalism and scholasticism.

Despite his outstanding contributions Schillinger is curiously unknown in music theory circles. Among those contributions are: a very systematic and complete theory of voice-leading by using simple circular permutation techniques and *modulo* arithmetic, an interesting theory of pitch scales and symmetrical divisions of one or more octaves[1], interesting investigations on the semantics of the music, enlightening opinions on orchestration and instrumentation. . .

However his most important contributions are probably in the field of the musical rhythm.

Rhythmic Resultants

A new and interesting idea of Schillinger is the *rhythmical resultant*[6].

---

[1] Symmetrical scales theory have been widely spread by others but Schillinger, if not the first was the one who systematized it to a much greater extend

Two different rhythms, when heard at the same time, create another which is the *resultant* of the two.

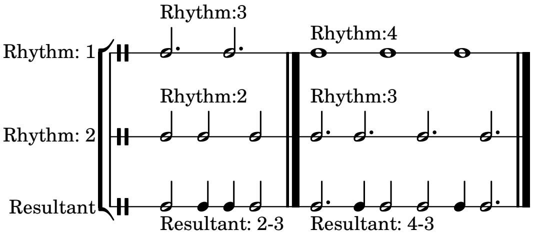

Figure 3.15: Some *rhythmical Resultants* according to the *Schillinger System of Musical Composition*[6]

Ligeti, in many of his works have used the resultant rhythms techniques in very practical ways. In his Second String Quartet, for instance, the uneven subdivisions of the beat serves to create an asynchronous yet still “calm”, animation.

In the fragment shown below[1] and in the following bars, we often get a stacking of subdivisions 4/5/6/7 of the beat.

That makes no single attack, except one occurring on the beat, of any part simultaneous with any other. This is a very effective and practical way to create an illusion of a faster playing speed. In such a beat, when players play simultaneously four, five, six and seven notes on a beat, the actual rhythm which is perceived is actually $4 + 5 + 6 + 7 = 22$ minus 3 (for the “on-beat” simultaneous attack) equals 19 distinct notes in a beat.

If the metronome speed is one second a beat or faster, the resulting “speed” of the notes, 19 notes per second would almost equal the perception threshold which is of 20 discernible “notes” per second, or 50 millisecond for a musical event.

As stated earlier[2] experiments made in the electro-acoustic music studios showed that for durations below 50ms. musical elements, in our perception tend to dissolve into a *continuum.*

This technique, being a highly *effective* and “economical” one, because it surpasses performers and instruments physical limitations for the creation of an over-fast animation, is extensively used by Ligeti. Most notable areas of its use are for creating over-fast *pizzicato* sections which would be otherwise impossible to play, over-fast trills and huge wave-like motions.

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[1] Figure:3.16, page:28

[2] See: section 1.5, page: 3.

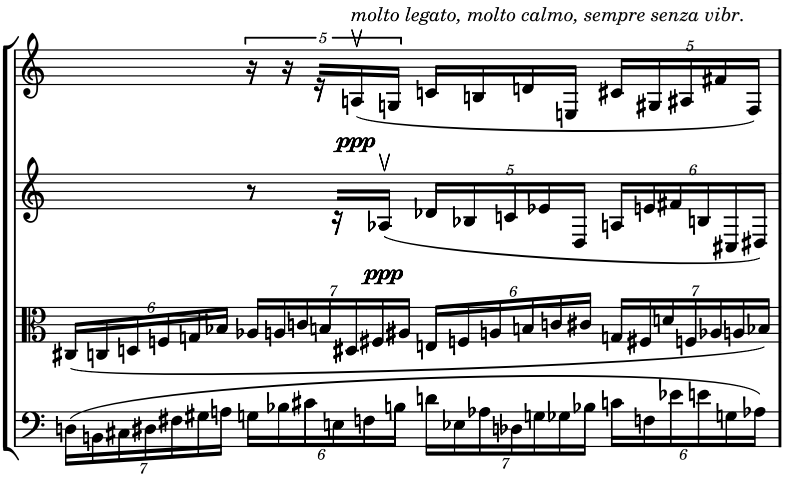

Figure 3.16: String Quartett N.2, First Movement, bar: 43. Uneven subdivisions of the beat.

In *Atmosphères*, at bars: 25-28, the *tutti-trills* are such an application. A gradually accelerating trill which starts at the First Violins and expands to the whole orchestra (except for the double-basses) is scored by using beat subdivisions ranging from 3 (eight-note triplets) to 15 (*quindidecimal tuplets of 32.nd notes.*

In the section which is the subject of this study[1] the rhythmical design of the parts is devised to prevent any synchronous attack and to avoid all kind of accentuation.

For this effect Ligeti did set in the up (Violins I) and bottom (Cellos) parts uneven *tuplet* beat-subdivisions. Five *(quintuplets of eights)* for Violins-I and three *(triplets of quarters)* for the Cellos. That will minimize the "risk" of having simultaneous attacks on the top and bottom parts to whose are perception is most sensitive.

The regularly subdivided inner parts (Violins II and Violas) uses the following rhythm palette:

The outer parts, Violins I and Cellos whose are set in *quintuplet* and *triplet* subdivisions are using for the most part the same rhythms as those shown above. Because of their beat subdivisions as *tuplets*, despite the huge 48-voice polyphony there are actually only a very few simultaneous attacks. Almost all parts move "independently".

A similar rhythm palette is used during the "raise" which occurs at bars 45 through 48. From bar 48, just before the entrance of the double-basses,

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[1] Bars: 44-53

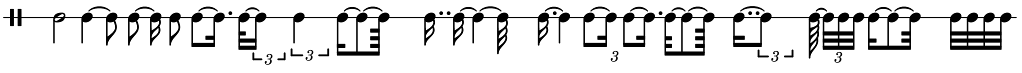

Figure 3.17: Sample rhythms of the Violins II and Viola parts

more *quintuplets* of 32nd. notes appear in the now even denser polyphony.

Double-basses are set in motion, yet not so fast due to the inertia of the instrument at the last two bars of the section.

The *crescendo* at bars: 52-53 is made stronger by the "shrinking" of the "cloud". As more individual instruments are joining on the same notes, near the end of bar:53 all instruments conglomerate in a very narrow range around middle-C.

The texture style created with the rhythms shown above, in the second Violins and Violas, is best described as an "ornamental style". Those rhythms combined with the neighboring intervals shown in the section: 3.4.1, page: 21 give the "cloud" its characteristic "inside-motion" effect.

The crowded appearance of the notated rhythm is intended to get even more "busy" sounding at the performance for each instrumentalist will inevitably slide from the exact notated values. Syncopes and *tuplets* will make for them impossible to be on the exact rhythm.

On the other hand, the detailed scoring will also prevent the passage to "deflate" by having musicians playing in synchronization with their neighbors.

3.5 Timbre and Spectrum

The whole piece, when viewed in a time-intensity display shows a very balanced set of peaks. The long opening section is well-balanced with the *coda.*

The section analyzed in this essay shows a regular *crescendo* shape.

Orchestrated for the strings section alone the passage is intended for a very homogeneous timbre. Except for the "shrinking" effect towards the end of the section, during the *crescendo* there is not any notable range shift. The "cloud" remain "stationary" in its outer design.

However, inside the homogeneous orchestral strings timbre, a subtle "coloring" effect is created.

The section starts *sul tasto* and *con sordino.* Mutes *(sourdines)* will remain on up to the end of the *crescendo.*

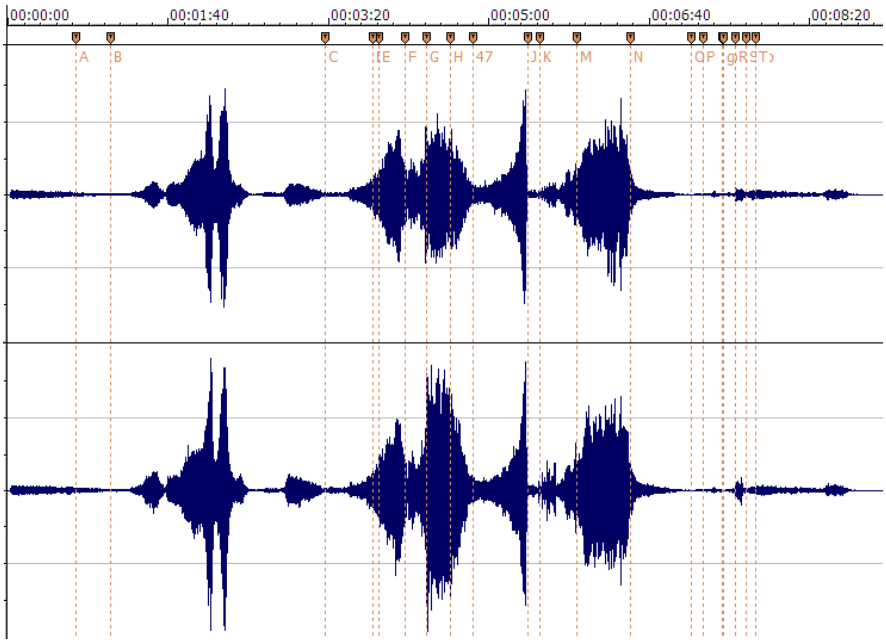

Figure 3.18: *Atmosphères* Time-intensity view of the complete piece.

Playing *sul tasto* gives the section its distinctive color. Then, at bars: 49-50; violins I, II and the cellos start getting one by one (beginning from the second violins) to play *sul ponticello.* A gradual shift of sound-color occurs.

This shift is notated as a very detailed process. It starts at the second violins then it "spreads" to the cello section and almost at the same time, starting from the Violin-I N.14 and going up to Violin-I N.1 it creates a gradual change in sound-color, as if the acoustical output from the orchestra was miked (recorded) and then modified, filtered through an electronic device.

The process is wanted to be really continuous, so when Violins I are getting "more and more" on *ponticello*, at the same time, cellos are getting back to normal playing position. This is noted *poco a poco ord.* in the score (bar: 49).

This color-shifting is also emphasized by the entrance of the Double Bass section in a cluster-like chord *sul tasto* and ***pppp*** at bar: 49.

From this time on, *ponticello* and normal playing is alternatively distributed among sections.

This creates a rather unique sound-effect which is best described by Ligeti himself:[1]

> One gets an additional subtlety in the timbre aspect by modifying the playing techniques. [...] By arranging to have not

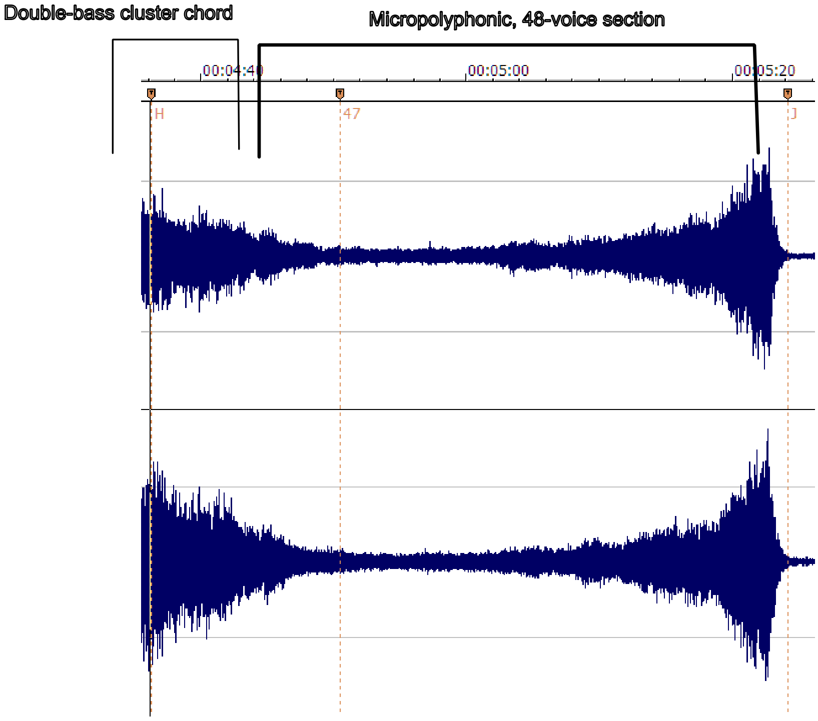

Figure 3.19: View of the section analyzed. After the stopping of the cluster in the double-basses the 48-voice polyphony builds up a big *crescendo*.

> all instruments playing “normal” or *sul tasto* at the same time, there is a diagonal shift such as at every moment another part of the texture is lightened by the “metallic” ray. [the apparition of higher frequency components in *sul tasto* playing] The indications appear on every instrumental part, but due to the great number of parts, we get an illusion of a continual transformation [of the timbre].

Sonogram and spectral views of an audio recording of the section show the gradual increase of higher frequency components created by the increase of *ponticello* playing.

Inside the thick compact “cloud” of sound shown here, the region from around 6,120 to 12,139Hz. is the overtones harmonic structure created by “normal” playing. The actual playing take place much lower than those frequencies, in around 200 to 1,600Hz. for a violin.

Even though neither a sonogram nor a spectral view can accurately display changes in performing techniques, for they can only show changes in the resulting spectrum of all the music (and the ambient noise), the darkened vertical bars shown in the Figure: 3.20 and the area with an increase

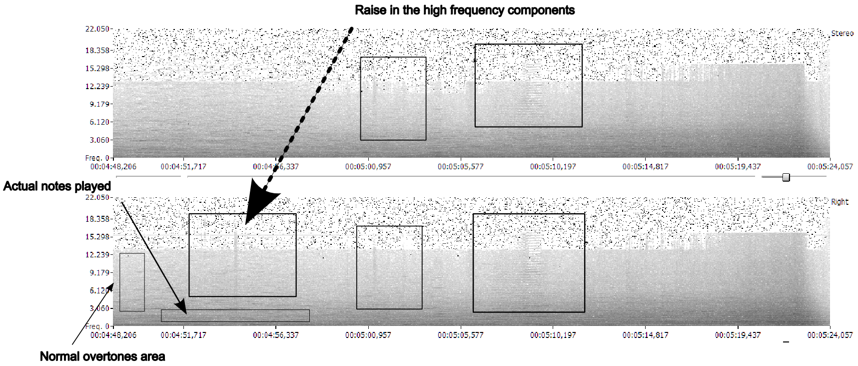

Figure 3.20: Sonogram view of the micropolyphonic section. Darkened areas show a condensation in the high frequencies at those times when several instruments are playing *ponticello*.

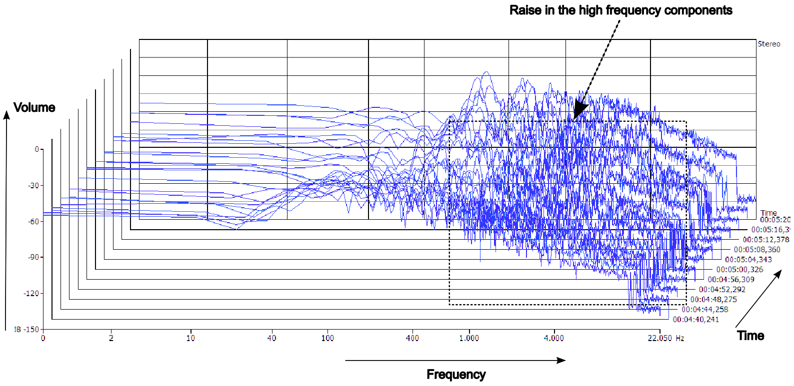

Figure 3.21: Spectral view of the same section. The jagged area also shows the increase in *ponticello* playing.

of jagged lines in the Figure: 3.21 nevertheless display an increase in the amount of higher frequencies created by an augmentation of the instruments shifting to *ponticello* playing.

Chapter 4

Conclusions

With *Atmosphères* composed in 1961, Ligeti has created an unique and extremely interesting orchestral scoring.

Xenakis with his sound-clouds and his *stochastic* procedures, Penderecki with his "sonism" as exemplified in his *Threnody for the Victims of Hiroshima* have, at approximately the same years, realized similar experimentations and composed works which can be thought of as analogous to *Atmosphères.*

However the similarities are only apparent and the structural compositional subtleties are not close to Ligeti's work.

In the case of Xenakis, the individual structures composing the "clouds" are actually not structures but "events" whose significances are of a limited extend. They have been "calculated" and "created" to fill the sound-space according to the rules given by the composer. The overall structure is a structure in the real sense but it is not made, nor it was meant to be made, by micro-structures. The result is a static "cloud". Because there are no micro-structures there is no evolution of them.

A similar appreciation can be made for Penderecki's sonic "entities". They are actually entities but they also lack of an evolutionary aspect.

Micro-structures are what makes Ligeti's work apart.

Another important conclusion is the uncanny and extremely creative way in which Ligeti has used his electronic-music studio experiments.

It is well known that the work done in the *WDR, RAI* and *ORTF* music research studios have been immensely important in the evolution of the present day's music language. While some composers like Boulez, Messiaen, have altogether abandoned working in the electro-acoustic field, others like Berio, Nono, Stockhausen always had "one foot in the studio".

However none, among those who "left" or those who "partially left" have so brilliantly took advantage of the electronic experiments to widen the instrumental and orchestral resources as Ligeti did.

Micropolyphony is only one of the techniques experimented on or discovered in the electronic-music studio and then “adapted” to orchestral writing. In many of his choral pieces, for instance *Lux Æterna* or in the *Requiem* the way he handled part entrances and exits is yet another such application. Parts are fading in and out as if manipulated by a mixing desk. Gradual shifts of tone-color is yet another adaptation of the electronic music studio techniques. This is an application of the *band-pass/reject* filters.

Chapter 5

Appendices

5.1 Granular Synthesis

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Granular synthesis is a basic sound synthesis method that operates on the microsound time scale. It is often based on the same principles as sampling but often includes analog technology. The samples are not used directly however, they are split in small pieces of around 1 to 50 ms (milliseconds) in length, or the synthesized sounds are very short. These small pieces are called grains. Multiple grains may be layered on top of each other all playing at different speed, phase and volume.

The result is no single tone, but a soundscape, often a cloud, that is subject to manipulation in a way unlike any natural sound and also unlike the sounds produced by most other synthesis techniques. By varying the waveform, envelope, duration, spatial position, and density of the grains many different sounds can be produced.

The result is usable as music, sound effects or as raw material for further processing by other synthesis or DSP effects. The range of effects that can be produced include amplitude modulation, time stretching, stereo or multichannel scattering, random reordering, disintegration and morphing.

Dennis Gabor researched how human beings communicate and hear. The result of his investigations was the theory of granular synthesis, although Greek composer Iannis Xenakis claimed that he was actually the first inventor of this synthesis technique (Xenakis, Formalized Music, preface xiii).

Curtis Roads is often credited as the first person to implement a digital granular synthesis engine. Canadian composer Barry Truax was one of first to implement real-time versions of this synthesis technique.

Some Granular Synthesis Software

- *REplay PLAYer* generative granular synthesis software for Mac
- *Granulab* real-time granular synthesizer for Win32
- *Chaosynth* cellular automata granular synthesizer by Eduardo Reck Miranda.
- *Vocal Modeler* Special vocal effect for Reaktor that uses granular synthesis.
- *crusherX-Live!* granular synthesis system for Windows
- *CDP* granular synthesizer from the *Composer's Desktop Project*
- *WSOLA* time scale modification of audio using granular synthesis
- *White FX* a granular effect for *Reaktor*
- *Audiomulch* a real-time audio processing tool which has some so called *contraptions* which offer granular synthesis.
- *Atomic Cloud* is an easy to use real-time grain cloud generator for Windows
- *Cecilia* provides one of the best frontends available for employing granular synthesis. It uses the *CSound* language.
- *Reason*, from *Propellerhead Software* released a virtual device called the *Malström*. The device, dubbed a "Graintable" synthesizer, combines granular and wavetable synthesis technologies.

5.2 Physical Modelling Synthesis

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Physical modelling synthesis is the synthesis of sound by using a set of equations and algorithms to simulate a physical source of sound. Sound is then generated using parameters that describe the physical materials used in the instrument and the user's interaction with it, for example, by plucking a string, or covering toneholes, and so on.

For example, to model the sound of a drum, there would be a formula for how striking the drumhead injects energy into a two dimensional membrane.

Thereafter the properties of the membrane (mass density, stiffness, etc.), its coupling with the resonance of the cylindrical body of the drum, and the conditions at its boundaries (a rigid termination to the drum's body) would describe its movement over time and thus its generation of sound.

Similar stages to be modelled can be found in instruments such as a violin, though the energy excitation in this case is provided by the slip-stick behavior of the bow against the string, the width of the bow, the resonance and damping behavior of the strings, the transfer of string vibrations through the bridge, and finally, the resonance of the soundboard in response to those vibrations.

Although physical modelling was not a new concept in acoustics and synthesis, having been implemented using finite difference approximations of the wave equation by Hiller and Ruiz in 1971, it was not until the development of the Karplus-Strong algorithm, the subsequent refinement and generalization of the algorithm into the extremely efficient digital waveguide synthesis by Julius O. Smith III and others, and the increase in DSP power in the late 1980s that commercial implementations became feasible.

Yamaha signed a contract with Stanford University in 1989 to jointly develop digital waveguide synthesis, and as such most patents related to the technology are owned by Stanford or Yamaha.

The first commercially available physical modelling synthesizer made using waveguide synthesis was the Yamaha VL1 in 1994.

While the efficiency of digital waveguide synthesis made physical modelling feasible on common DSP hardware and native processors, the convincing emulation of physical instruments often requires the introduction of non-linear elements, scattering junctions, etc. In these cases, digital waveguides are often combined with FDTD, finite element or wave digital filter methods, increasing the computational demands of the model.

Examples of physical modelling synthesis:

1. Karplus-Strong string synthesis

2. Digital waveguide synthesis

3. Formant synthesis

5.3 Csound

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Csound is a computer programming language for dealing with sound, also known as a sound compiler or an audio programming language. It is called Csound because it is written in the C programming language, as opposed to some of its predecessors.

Csound was originally written at MIT by Barry Vercoe, based on an earlier language called Music360, developed by Max Mathews at Bell Labs. It is free software, available under the LGPL. Its development continued throughout the 1990s and 2000s, led by John ffitch at the University of Bath, resulting in the launch of Csound 5 in February, 2005.

Many developers have contributed to it, most notably Istvan Varga, Gabriel Maldonado (who developed a variant of the system, CsoundAV, which includes image and graphics processing extras), Robin Whittle, Richard Karpen, Michael Gogins, Matt Ingalls, Steven Yi and Victor Lazzarini.

Csound takes two specially formatted text files as input. The orchestra describes the nature of the instruments and the score describes notes and other parameters along a timeline. Csound processes the instructions in these files and renders an audio file or real-time audio stream as output.

Csound Granular Synthesis *opcode* Example

This text, copied from the Csound Manual[4] shows the various controls for one of the Csound's Granular Synthesis *opcodes*[1] **grain3** *Accessed: February 15, 2008*

grain3

grain3 Generate granular synthesis textures with more user control.

Description: Generate granular synthesis textures. *grain2* is simpler to use but *grain3* offers more control.

Syntax: `ares grain3 kcps, kphs, kfmd, kpmd, kgdur, kdens, imaxovr, kfn, iwfn,  kfrpow, kprpow [, iseed] [, imode]`

Initialization:

imaxovr maximum number of overlapping grains. The number of overlaps can be calculated by (*kdens* * *kgdur*); however, it can be overestimated at no cost in rendering time, and a single overlap uses (depending on system) 16 to 32 bytes of memory.

iwfn function table containing window waveform (Use *GEN20* to calculate *iwfn*).

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[1] **opcode:** Operation code, codified command name performing a defined action in the Csound language

iseed (optional, default=0) seed value for random number generator (positive integer in the range 1 to 2147483646 (231 - 2)). Zero or negative value seeds from current time (this is also the default).

imode (optional, default=0) sum of the following values:

- 64: synchronize start phase of grains to *kcps*.
- 32: start all grains at integer sample location. This may be faster in some cases, however it also makes the timing of grain envelopes less accurate.
- 16: do not render grains with start time less than zero. (see the image below; this option turns off grains marked with red on the image).
- 8: interpolate window waveform (slower).
- 4: do not interpolate grain waveform (fast, but lower quality).
- 2: grain frequency is continuously modified by *kcps* and *kfmd* (by default, each grain keeps the frequency it was launched with). This may be slower at high control rates. It also controls phase modulation (*kphs*).
- 1: skip initialization.

Performance:

ares output signal.

kcps grain frequency in *Hz*.

kphs grain phase. This is the location in the grain waveform table, expressed as a fraction (between 0 to 1) of the table length.

kfmd random variation (bipolar) in grain frequency in *Hz*.

kpmd random variation (bipolar) in start phase.

kgdur grain duration in seconds. *kgdur* also controls the duration of already active grains (actually the speed at which the window function is read). This behavior does not depend on the *imode* flags.

kdens number of grains per second.

kfrpow this value controls the distribution of grain frequency variation. If *kfrpow* is positive, the random distribution (x is in the range -1 to 1) is $abs(x)^{((1/kfrpow)-1)}$ for negative *kfrpow* values, it is $(1 - abs(x))^{((-1/kfrpow)-1)}$ Setting kfrpow to -1, 0, or 1 will result in uniform distribution (this is also faster to calculate). The image below shows some examples for kfrpow. The default value of kfrpow is 0.

kprpow distribution of random phase variation (see *kfrpow*). Setting *kphs* and *kpmd* to 0.5, and *kprpow* to 0 will emulate *grain2*.

kfn function table containing grain waveform. Table number can be changed at *k-rate* (this is useful to select from a set of band-limited tables generated by *GEN30*, to avoid aliasing).

5.4 Stochastic

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A stochastic process, or sometimes random process, is the counterpart to a deterministic process (or deterministic system) in probability theory.

Instead of dealing only with one possible "reality" of how the process might evolve under time (as is the case, for example, for solutions of an ordinary differential equation), in a stochastic or random process there is some indeterminacy in its future evolution described by probability distributions. This means that even if the initial condition (or starting point) is known, there are many possibilities the process might go to, but some paths are more probable and others less.

In the simplest possible case (*discrete time*), a stochastic process amounts to a sequence of random variables known as a *time series* (for example, Markov chains). Another basic type of a stochastic process is a random field, whose domain is a region of space, in other words, a random function whose arguments are drawn from a range of continuously changing values.

One approach to stochastic processes treats them as functions of one or several deterministic arguments (*inputs*, in most cases regarded as *time*) whose values (*outputs*) are random variables: non-deterministic (single) quantities which have certain probability distributions.

Random variables corresponding to various times (or points, in the case of random fields) may be completely different. The main requirement is that these different random quantities all have the same "type". Although the random values of a stochastic process at different times may be independent random variables, in most commonly considered situations they exhibit complicated statistical correlations.

Familiar examples of processes modeled as stochastic time series include stock market and exchange rate fluctuations, signals such as speech, audio and video, medical data such as a patient's EKG, EEG, blood pressure or temperature, and random movement such as Brownian motion or random walks. Examples of random fields include static images, random terrain (landscapes), or composition variations of an inhomogeneous material.

References

[1] Ligeti, György. 2001. *Neuf Éssais Sur La Musique*. Genève: Éditions Contrechamps.

[2] `http://en.wikipedia.org`.

[3] Xenakis, Iannis. 1963. *Musiques Formelles*. Paris: Éditions Sock.

[4] Vercoe, Barry, John ffitch, Jean Piché, Peter Nix, Richard Boulanger, Rasmus Ekman et al. 1986, 1992. Massachusetts Institute of Technology.

[5] Schillinger, Joseph . `http://en.wikipedia.org/wiki/Joseph_Schillinger`.

[6] Schillinger, Joseph. 1941. *The Schillinger System of Musical Composition*. New York: Carl Fisher Inc.

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