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Cellular Music: a Novel Music-Generation Platform based on an Evolutionary Paradigm

Relatore: Prof. Augusto Sarti
Correlatori: Ing. Clara Borrelli, Ing. Luca Comanducci

Tesi di Laurea di:
Matteo Manzolini, matr. 905054

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Abstract

Computer-Assisted Composition techniques are widely used in the musical world, and a wide use of Genetic Algorithms and Neural Networks has been made to support artistic creativity, however their use in order to create a new musical language has never been explored. In this thesis we wanted to present a novel musical framework, that is a compositional technique based on the use of Artificial Intelligence algorithms for Computer-Assisted Composition and inspired by the biological life cycle of microorganisms cultured in a Petri dish, in which melodic cells evolve and interact with each other within musical habitats. For application to the field of tonal music, an algorithmic technique of melodic synthesis based on Schenkerian Analysis has also been formalized. An interactive application was therefore created in Processing, Python and Supercollider that makes use of Genetic Algorithms and Neural Networks for the implementation of cellular music and subsequently an evaluation survey was carried out on a sample of professional musicians.

Sommario

Le tecniche di composizione assistita sono ampiamente diffuse nel mondo musicale, ed ampio uso è fatto degli algoritmi genetici e delle reti neurali in supporto alla creatività artistica, tuttavia un loro utilizzo al fine di creare un nuovo linguaggio musicale non è mai stato esplorato. In questa tesi si è voluto presentare un inedito framework musicale, ovvero una tecnica compositiva basata sull'uso di algoritmi di intelligenza artificiale per la composizione assistita e ispirata al ciclo di vita biologico di microrganismi allevati in capsula di Petri, in cui cellule melodiche si evolvono ed interagiscono tra di loro all'interno di habitat musicali. Per l'applicazione all'ambito della musica tonale è inoltre stata formalizzata una tecnica algoritmica di sintesi melodica basata sull'Analisi Schenkeriana. È stata dunque realizzata un'applicazione interattiva in Processing, Python e Supercollider che fa uso di algoritmi genetici e reti neurali per l'implementazione della musica cellulare e successivamente è stata svolta un'indagine valutativa su un campione di musicisti professionisti.

Acknowledgements

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Chapter 1

Introduction and motivations

1.1 Context and Motivations

The idea behind the realization of this work was originally conceived in the context of creative programming and computing, a field of study whose purpose is both the use of the most recent technological innovations to support artistic installations, as well as the improvement of the tools available to artists to cope with an ever growing demand for means with which to express their creativity. In fact, it is no coincidence that the most recent and innovative artistic musical movements, increasingly tend to be strengthened by the support of technology.

For years now, in the musical field, it has been widely made use of Computer Assisted Composition (C.A.C.), through which it is possible for a composer to facilitate his work in the most practical aspects, thus opening up new avenues to his creativity and artistic vein.

Until now, however, the technological tools aimed at computer music have limited themselves to intervening in support of composers or performers in the field of preexisting musical genres, facilitating or enhancing their creativity and allowing a deeper artistic exploration. The enormous variety of uses and potential of these instruments, however, has never been duly exploited in a more direct way, aimed at the creation of new musical structures based on them.

With this work we therefore wanted to explore the possibility of exploiting technologies usually adopted for assisted composition in a totally different way, thus creating a novel music-generation platform that can subsist thanks to their existence and use. This compositional paradigm therefore presents itself as a framework of musical rules and principles that can be applied to the most disparate contexts, giving composers new possibilities for expressive research and opening new potential stylistic avenues, having such technologies not as an optional support, but as the real supporting structure.

1.2 Summary of the work

The music framework was born from the intuition that simple musical cells can be treated as if they were microorganisms raised in a Petri Dish[1].

The system consists of a culture medium, that is a two-dimensional area divided into different regions, called habitats, each one of which represents a bass note, associated with the sound of a drone or a pad[2].

A melodic cell, which can be composed directly by the composer or created autonomously or semi-automatically, is inserted in the ecosystem in an arbitrary position. This cell is a fragment of a melody, consisting of a sequence of musical notes with constructive properties[3].

The presence of a cell within the system activates the sound of the cell itself, which can repeat itself cyclically but not consecutively, while the position of the cell in the plane defines its own timbre.

At each moment, the cell makes an assessment of how much it is suitable for living in the habitat in which it is located. This fitness function can depend on various aspects, such as, for example, the belonging or not to a tonal music system.

Based on this value, the cell will be subjected to a different acceleration which, in the case of low fitness, will lead it to move in the ecosystem in search of a habitat that allows for better suitability, while in the case of high adaptation, it slows down and in this way it has the possibility of developing and/or evolving.

The evolution, which takes place according to the degree of adaptation at the moment considered, consists in the variation of the pitch of one or more notes, their duration or their intensity. Under particularly favorable conditions, the cell can grow, adding a new note to the head or tail. In this way, even if the fitness calculation were to involve little movement, evolution itself would cause it, adding an "unpredictable" component.

[1] A Petri Dish, named after its inventor, is a shallow transparent lidded container that biologists use to hold growth medium in which cells can be cultured.

[2] A musical drone is a sustained sound, note or tone cluster, while the synth pad is a more articulated electronic drone. This subject will be described in section 3.2.1.

[3] See chapter 2.3.1, "What is Melody".

Evolution can vary greatly depending on the stylistic context, but it can be implemented through the use of a genetic algorithm that will tend to gradually modify the considered cell in order to improve its physical shape in the particular habitat in which it is at the moment in question, and at the same time inserting the possibility that the cell undergoes a further genetic mutation.

If a cell grows, reaching dimensions that exceed predefined limits, the cell will undergo mitosis, dividing into two distinct cells, which will take different directions and independent lives, each with a new fitness value and a new evolutionary process.

The meeting of two cells involves their mutual evaluation, with a fitness system like the one already described above, always strictly dependent on the stylistic context. In the case of tonal music, addressed in detail in this thesis, this evaluation takes place according to the principles of tonal architecture defined in Schenkerian analysis. In practice, the ability of the cells, united, to create a theoretically correct melody on a constructive level will be verified.
If the cells are mutually compatible, they will merge generating a melody which, like a cell, will carry out its own life cycle in the musical ecosystem and can merge with other melodies. Unlike a simple cell, however, in addition to having no length limits, a melody will not be subject to fission.

To avoid excessive overcrowding of the ecosystem due to the presence of too many cells, the insertion of an apoptosis function is envisaged, which occurs when a cell, in a given time interval, has not found any other compatible cell with which to fuse or was not subjected to mitosis. If so, the cell will die and disappear from the system.

The composer has the possibility to intervene on the system at any time by creating and inserting new cells, removing others or creating disturbances in the motion of those present to avoid moments of stasis or according to his own personal aesthetic tastes.

1.3 Organization of the thesis

The thesis will be structured as follows:

- In chapter 2 the musical and technological context will be exposed, with references to the state of the art in the various elements treated. A summary of musical and musicological theory will also be made, both in the tonal field and in the atonal field, as well as the ways in which such theory is modeled and reworked in the context of this thesis. This is aimed at a more extensive understanding of the reasons for certain choices made in the formalization of the framework. Particular emphasis is placed on the theory of Schenkerian analysis for tonal melodic synthesis.

- In chapter 3 there will be a detailed presentation of the concept of cellular music, starting from the description of the fundamental structures that constitute it, that is the musical cell and the acoustic habitat, and subsequently describing the lifecycle of an isolated cell and the interaction between the several musical elements present in the musical ecosystem.
- In chapter 4, the ways in which the mutual evaluation of two cells or two melodies will be treated, as well as how the process of their respective fusion in the creation of a new melody can be achieved, in a strictly tonal context, using the concepts of Schenkerian analysis presented in chapter 2 to achieve a melodic synthesis consistent with the principles of tonality.
- In chapter 5 will be presented a software implementation, realized with Supercollider, Processing and Python, of the cellular music concepts previously exposed, both in the tonal and in the atonal field, with particular emphasis on the use of the technological tools previously introduced.
- In chapter 6 the results of the application evaluation of the framework will be outlined and analyzed through demonstrative implementation.
- In chapter 7, finally, will be reported the conclusions and possible future developments that can further improve the concepts exposed or extend them to different application fields will be proposed.

Chapter 2

Background and musicological overview

In this chapter, it is first briefly introduced the technological background of this thesis, namely that of Computer-Assisted Composition. It follows an introduction to the fundamental musical and musicological concepts that have been taken into consideration in the conceptualization and in the subsequent implementation of the compositional paradigm presented in this thesis.

2.1 State of the art

The work produced in this thesis, although focused on the principles of music theory that constitute the compositional paradigm of cellular music, falls within the broader scope of Computer Aided Composition (CAC) and of Automatic Music Composition, which is part of the field of study in Artificial Intelligence (AI). In particular, it is based on the use of genetic algorithms and Variational Autoencoders (VAE) for the creation, assessment and optimization of melodic figures.

Being novel both in the aims and in the approach to the realization, it is difficult to search for previous works with which to be able to make a comparison in its entirety. However, in this section, will be listed significant works for compositional purpose that adopt a similar approach in the use of Genetic Algorithms and Neural Networks, for the automatic or assisted composition of melodies.

2.1.1 Automatic music composition using genetic algorithms

Algorithmic Composition was born, as well digital sound synthesis, around the middle of the twentieth century, with its major developments being "MUSIC I", the first real music program being able to play a single tune [33], and the "Illiac Suite for string Quartet", the first musical piece entirely written by a computer[5].

Of particular interest for the field of automatic composition are Evolutionary algorithms (EAs), inspired by the Darwinist biological model of evolution and natural selection, applying the principles of the biological mechanics – such as selection, reproduction, mutation etc. – to a problem and trying to find an optimal solution. The algorithm starts with a set of candidate solutions, some of which are selected according to a fitness function value. Crossover and mutation operators are applied on candidates and the process is repeated iteratively until an optimal solution is found [19].

An approach to compose music using genetic Algorithms is presented by Matic [19], whose aim was to produce short pleasant compositions by exploiting all the sets of all individuals, rather than by optimizing the results. The individuals of the initial population possessed some predefined rhythms, the crossover operation was omitted and, in its stead, three different types of mutations were used and applied on the best individuals multiple times to improve them. The used fitness function was based on different criteria on the various measurable musical elements (pitch, duration, etc.) and the generated music was evaluated by computing the similarity with reference individuals. The approach resulted in effectively pleasant compositions with good rhythms, however this approach was somehow rigid, as omitting the crossover operator greatly limited the convergence towards an optimal solution. Also, the music produced was not submitted to expert musical judgement.

One of the most interesting software models in the field of automatic music composition was *GenJam*, implemented by Biles in 1994[2]. It was developed using a genetic algorithm that sported an interactive fitness function, where each individual is evaluated by a user who listens to the resulted music and assigns it a fitness value. The system also had two different populations instead of one, where the first represented the musical phrase population and the second one the measure population, where each individual in it is mapped to indices in the first one. This version of GenJam had two major weaknesses, as the notes of the melodies had to be only eighth notes and could be chosen only within 14 pitches.

In 2008, Oliwa et al.[32] developed a knowledge-based evolutionary music system. It was based on Time Delay Neural Networks (TDNN) and Ward Nets on a probabilistic finite state machine (FSM) and was provided with internal knowledge of the structure of the composed music. This system used genetic algorithms and the "abc" music notation to evolve the four types of classic rock musical voices: lead guitar, rock organ, drums and rhythmic guitar. It had 5 genome types with different integer configurations and a specific set of fitness functions. The training data of the Neural Networks consisted of 19 songs written in "abc" language, translated into MIDI, and the Ward Net was trained for over 72000 epochs with an error of 0.0006718 on the training set. The results showed that the Neural Network was oscillating more often between extreme notes with large intervals between them and was not able to memorize the whole song.

Chen[4] used a Recurrent Neural Network, specifically a Elman's one, to generate melodies, coupled with a genetic algorithm to maximize the chance of producing good tunes, where the fitness function was determined by a melodic constraint on tonality and rhythm. The melody could have notes ranging in three octaves and of durations between the sixteenth note and the whole, and the adopted constraints – for a total of seven – involved the composing style and the rules of classical theory. These constraints, which were singularly activated, affected the value of the fitness, and some had the possibility to dominate others with the relevance of their contribute to such value. The optimal result in the first experiment was obtained after 750 generations, while in the 2nd one it happened after the 200th generation.

2.1.2 Deep Interactive Evolution

In 2018 Bontrager et al.[3] published a particularly interesting article in which they presented *Deep Interactive Evolution*, an approach that integrates the use of Generative Adversarial Networks (GANs), a class of methods in which two neural networks are competitively trained within a minimax game framework [9]. with Interactive Evolutionary Computing (IEC).

Although not specifically created for the use in the musical field, the system allows the creation of realistic artifacts through the implementation of two pre-trained Deep Neural Networks (DNN), coupled together so that one is generative

and one is discriminative.
The discriminative network has the task of learning to distinguish the images produced by the adversary DNN from those belonging to a given dataset, while the generative one learns to deceive the other, in order to produce artifacts of the highest possible quality.

Subsequently, a population of individuals produced by the GAN is shown to a user, who evaluates it according to their preferences by selecting their favorite artifacts.

At this point a genetic algorithm is implemented, which performs the crossover between pairs of individuals, or which randomly selects elements of their latent variables to create a new set with which the GAN is updated. The system then proceed with the generation of a new population that will be more compliant with the preferences expressed by the user in the previous evaluation, and the process is repeated iteratively until an optimal solution is selected.

The system has proved to be very powerful and particularly suitable for creating or transforming realistic-looking images, but it can also be used in the musical field and in the generation of 3d objects.

2.1.3 MusicVAE

In many respects similar to GAN, but different in philosophy that drives the loss metric and in architecture, Variational Autoencoders (VAEs) has proven to be an effective model for producing semantically meaningful latent representations for natural data, and have found use in the field of automatic music composition in the form of MusicVae, presented in 2019 by Roberts et al. [28].

A variational autoencoder[15] is a refinement of an autoencoder, with the added constraint that the encoded representation, that is the latent variables, follow some prior probability distribution, usually a Gaussian distribution.

Due to the fact that VAE models usually have difficulty modelling sequences with a long-term structure, Roberts et al. adopted a hierarchical decoder, that proceeds by outputting the embeddings for subsequences of the input first, and then utilizes such embeddings for the generations of each subsequence independently, encouraging the model to utilize its latent code.

This approach proved very efficient in both the creation and blending of musical pieces of various duration, including melodies, rhythms and chord sequences.

2.2 Musical Background

In this section we will briefly deal with the theoretical concepts and principles of tonal and atonal music, aimed at greater clarity of the reasons that led to the formulation of the theory of cellular music. Following the practice commonly adopted by music theorists, it is necessary to start from the physical foundations of harmony, with a brief introduction on the concepts of tonal and atonal music, as well as on the rules that govern their composition.

2.2.1 Tonal Music

Although today it can be said with certainty that the vast majority of existing music belongs to the category of tonal music, this concept was not developed before the sixteenth century, when Gioseffo Zarlino first formulated the theory of the building of the triad[36], based on the much older theories on the sound spectrum and the harmonic series, dating back at least to the sixth century BC.

Harmonic bases

Since ancient times it has been known that every complex sound is constituted by the sum of several oscillations connected to each other by belonging to the harmonic series, and for this reason called *harmonics*. This oscillations take also the name of "partials", where the first harmonic is called "fundamental tone", which defines the musical pitch, followed by an infinite amount of "overtones". Despite the infinite theoretical amount of harmonics, the human ear is able to clearly perceive only the first five overtones, which therefore acquire a substantial relevance[29].

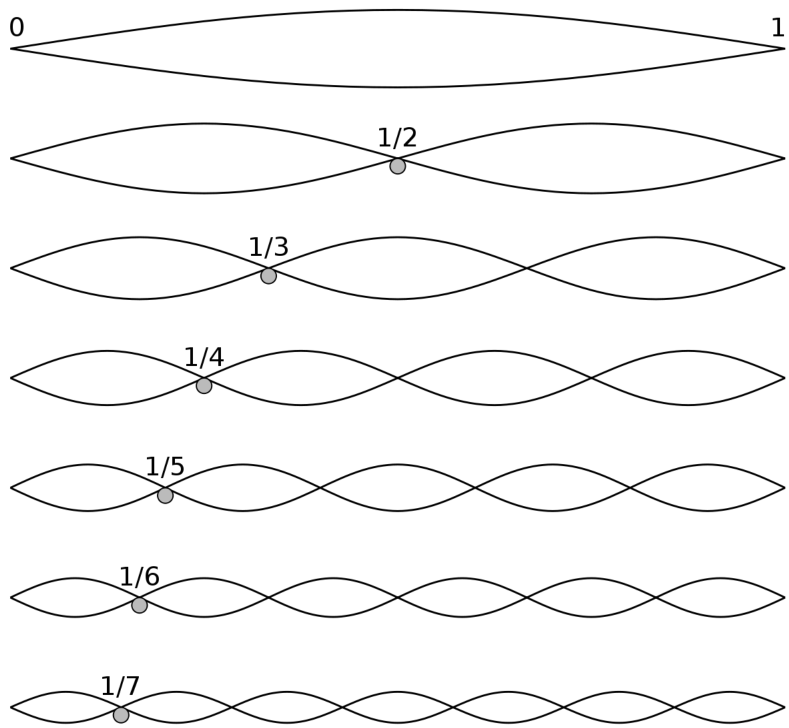

Figure 2.1: Harmonics of a string showing the periods of the pure-tone harmonics.

As can be seen from the image, the first harmonic after the fundamental frequency, and therefore the most perceivable, is an oscillation set at twice the frequency value of the previous one, which, to the human ear, will sound with the highest degree of consonance with the previous one, and is called "octave". This value, doubled from time to time, occurs throughout the whole spectrum of the sound, until the level is so low that it is no longer perceptible.
The second overtone, precisely following the ratios of the harmonic series, oscillates with a frequency three times higher than the fundamental one and the third one represents another octave from the first overtone. The distances between these first three harmonics constitute the fundamental principle of tonality, identifying in fact the so-called "perfect intervals", that are the octave, the interval of fifth, between the first and the second overtone, and the interval of fourth,

between the second and the third overtone.
Continuing further on, considering the last two of the audible harmonics, it is finally possible to find the last two fundamental elements that are employed to define the concept of tonality, namely the presence of a major third interval, followed by a minor third. These last partial forms an interval of fifth with the third overtone.

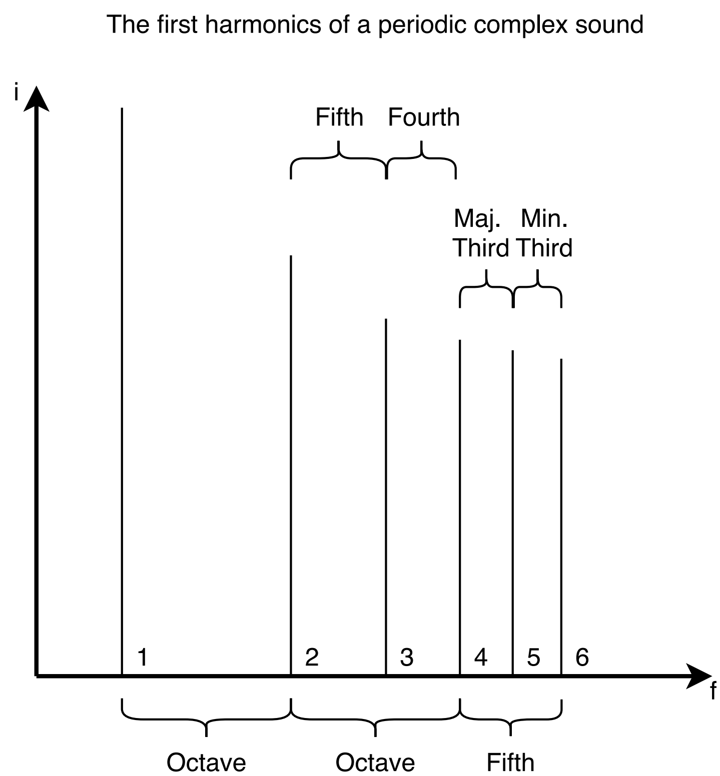

Figure 2.2: The first six harmonics with the relative intervals.

It is these intervals (the octave, fifth, fourth, major third and minor third) that completely define the theory of tonal music.

The musical scale

Having noticed the periodicity of the octave interval in the harmonic series, since ancient music it has been decided to uniquely identify a subdivision of sounds within such span [10], assigning them precise values calculated from their appearance as the harmonic series progresses. In fact, by putting in succession six consecutive intervals of perfect fifth, we obtain all the seven notes that, rearranged within a single octave, identify what is called "diatonic musical scale".

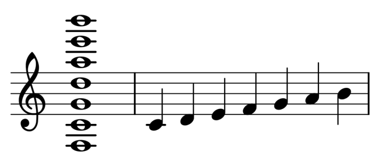

Figure 2.3: Diatonic scale in standard notation as expansion of a succession of fifths.

Continuing the succession of intervals of perfect fifth, after another six steps, the tonic shows itself again. By rearranging these intervals within an octave, the chromatic scale is obtained, which constitutes the fundamental pillar of most, if not all, western music. This complete cycle, which divides the intervals linearly between a note and its higher octave, is defined as the circle of fifths, and plays a fundamental role in the birth of tonality. In fact, independently from the starting pitch, the following of the cycle is always the same. This denotes the formal equivalence of the starting point and the solidity of such system, which is derived from natural rules and efficiently transposed in an efficient human-playable musical language.

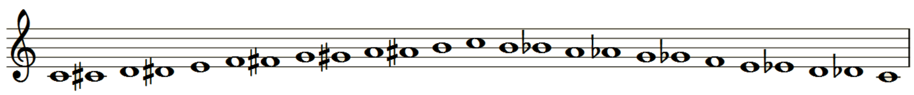

Figure 2.4: Ascending and Descending chromatic scale.

Comparing the two scales, we can see how the first is made up of five *tone* steps, namely intervals where an intermediate one, present in the chromatic scale, is skipped, and two *semitone* jumps, which means made up of two consecutive notes present in the chromatic scale. The tone intervals are distributed in such a way as to maximize the distance between the two semitone intervals, but beyond this constraint, any heptatonic scale consisting of this quantity of tone and semitone intervals is considered a *diatonic scale.*

The tonal system

If for the first millennia of musical development the use of the diatonic system prevailed, closely linked to the use of modes[1] of this scale, with the advent of polyphony the need arises for more stringent rules that dictate to musicians the best ways to combine different sounds in a coherent way. Thus the use of modal scales and simple polyphonies such as the *organa* [2], is progressively abandoned in order to obtain a clearer musical direction, and the relationship between the tonic and its fifth interval assumes a role teleologically more inclined to a cadential resolution.

All music begins to be composed in two particular ways of the diatonic scale, namely the ionic one, characterized by the following sequence of tones and semitones:

TONE - TONE - SEMITONE - TONE - TONE - TONE - SEMITONE

and the aeolic mode, which starts from the sixth grade of the ionic scale:

[1]Diatonic modes are scales that maintain the distances of the diatonic scale even with a different ordering.

[2]from *Organum*: singing technique developed in the Middle Ages, which, in its standard form, involved only two voices: a Gregorian melody, superimposed on a version of itself displaced by a consonant interval, usually a perfect fourth or fifth.

TONE - SEMITONE - TONE - TONE - SEMITONE - TONE - TONE

Regardless of the scale, the degrees identifying the seven notes, identified through the Roman numeration, are thus called:

I - Tonic

II - Supertonic

III - Mediant

IV - Subdominant

V - Dominant

VI - Submediant

VII - Leading Tone or Subtonic

Based on these scales, which are called "tonal scales", or respectively "major scale" and "minor scale", the composers realized that the first examples of polyphony based on the progression of natural harmonics had the tendency, whenever a fifth interval appeared, to spontaneously "resolve" on the tonic, or rather that the musical tension created by it made the acoustic effect of the piece extend towards that direction. Similarly, the various degrees of the scale lead towards specific other degrees, and this tendency is more pronounced if such notes are played simultaneously. These cadential rules of superposition of different sounds were therefore formalized in the theory of the triads.

The triad

A triad is the simplest type of chord necessary and sufficient to describe a cadence-like musical sequence, that is a series of chords in which there is a precise acoustic effect of tension and resolution. It consists of two intervals of third, which can be respectively major and minor, thus identifying the tonic, the mediant and the dominant of a major scale, if the lower interval is a major third, or of a minor scale, if this interval is a minor third. If the triad is built

by stacking two intervals of major third, it takes the name "augmented" triad, while two minor thirds superimposed will consitute a "diminished" triad
According to this principle, it is possible to build triads, major and minor, starting from each of the seven degrees that make up a tonal scale.

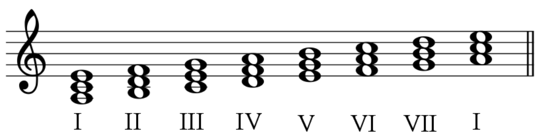

Figure 2.5: Triads built on each degree of a natural A minor scale.

Of these triads, which, in the specific key, take the names of the degree of the scale on which they are built, great importance is assumed by the tonic, dominant and subdominant chords, as they are built on the degrees corresponding to the first harmonic intervals of the harmonic spectrum of the tonic.
All of this chords can be ordered into cadences, or chord sequences, built on the degrees of a particular scale, endowed with a particular resolving tendency, and therefore used to conclude a musical phrase or a fragment of it.
Each cadence, which can be of a different nature according to the chords that constitute it, being always concluded by a chord built on the root of a musical scale, represents one of the most important elements of the concept of tonality, and which therefore define it. The art of placing chords in succession according to such established rules - and according to many other ones developed over the centuries - is called "Harmony".

Definition of Tonality

Having defined the chords built on the degrees of a scale, and which of them are the most important, it is possible to make a simple observation. Each one of these chords, perhaps with the exception of the sensible chord, as it is a diminished triad, can be considered "tonic" of another key, that is to say the main chord of a musical segment built on a different scale from the one currently used. The possibility of moving from a key to a new one, based on a chord built on one of its degrees, is simply called "modulation" [3].

Tonality, in the conventional sense, may be defined as a central key in which a musical work opens and closes, but which serves as the point from which to modulate to various other keys. A broader definition than this, and one which may be more acceptable, is given by Schönberg. He defines tonality as "the art of combining notes in such successions and such harmonies or successions of harmonies, that the relation of all events to a fundamental note is made possible." [1]

The conventional concept of tonality may be considered as based on the following two principles:

1. The establishment of a "tonal center," or "fundamental note," i. e., the principal key of a given composition;
2. The set of rules, derived from the theory of the natural harmonics, that relate other keys, employed as subservient to the principal key, usually explained by the theory of modulation.

More on the theory of tonal music composition will be discussed in section 2.3 on Musical Modeling.

[3] In fact, there can be different definition of modulation, based on the specific time period and particular musical style, but this one is nonetheless an accepted one, albeit, perhaps, debatable.

2.2.2 Fundaments of Tonal Architecture: the Schenkerian Analysis

At the beginning of the twentieth century, the austrian composer and music theorist Heinrich Schenker formulated a new way of conceiving the architecture of tonal music, aiming at a more precise harmonic and contrapuntal analysis. He started from the assumption, derived from a well-established musical conception, that in a piece of tonal music it is possible to identify a single tonality, where the so-called modulations can be considered as "lying within it". With a picturesque definition, Schenker therefore defines tonality as "the life of one tone as it governs the entire work" [14]. Such life is described, as done in section 2.2.1, starting from the definition of the harmonic properties of a periodic sound, which Schenker calls *Klang*[4].
But as the natural principle of sound structure is "simultaneity", as expressed in the harmonic spectrum of a sound, for expressive and convenience purposes reduced to the triadic system, Schenker differentiate the artistic adaptation of this principle, which is "succession". Thus, a new way of seeing all tonal musical compositions is born.

The three layers

One of the most important aspects of schenkerian analysis is that it does not view the work as built from a unique succession of events, but as the growth of new ones from within events placed at a lower level. Therefore, the goal of Shenkerian analysis is to understand the structure of a piece of music as a superposition of different levels, each one being able to be extracted from the upper one through specific musical operations. Schenker identifies three main structural levels, or layers, which he calls *Schichten*, that, composed one atop of each other, make up a whole musical piece, the lower of them being the *Ursatz*, the "fundamental structure". This is also called the *Hintergrund*, or "background layer".

The most superficial layer, and so the one that strikes our hearing the most, is what is called the *Vordergrund*, "surface layer" or "foreground". This represent everything that's happening in the analyzed music piece in all its detail.

Between the Ursatz and the Vordergrund, lies a third middleground, called

[4]In schenkerian theory, a Klang, meaning "Sound" in german, identifies a tuned sound composed by the fundamental frequency and at least its first five overtones.

Mittelgrund, which is composed of all the most important notes which, once all the superficial decorative structures are removed, give the music its meaning. This process of moving from the Vordergrund to the Mittelgrund is called *Auskomponierung*, or "Reduction". This procedure, although with different rules, is also applied to the Mittelgrund to extract the Hintergrund, that is a structure so basic as to be, according to the Schenkerian analysis, common to all musical compositions that can be considered belonging to tonal music.

Thus, Shenkerian analysis can be summarized as this process of reduction from the actual music of the surface level down to its most basic fundamental structure, common to all musical pieces.

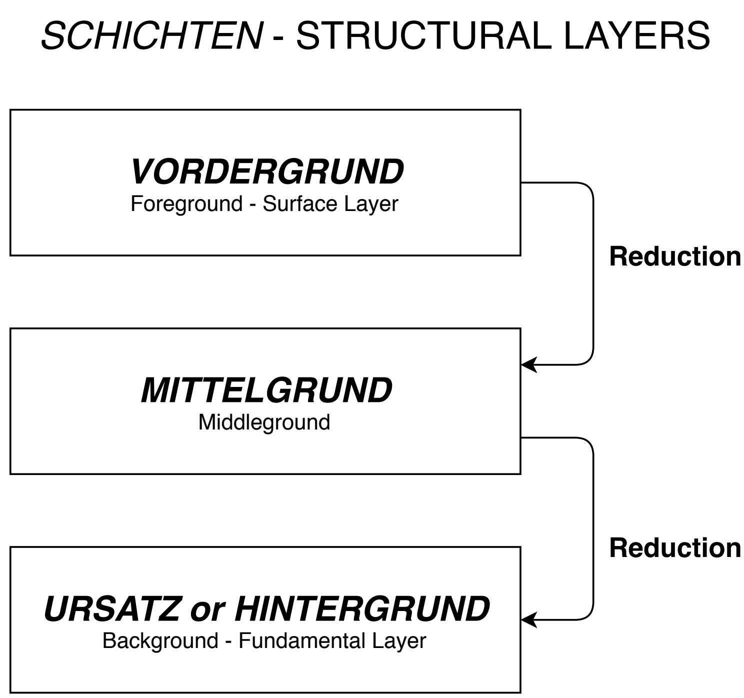

Figure 2.6: The three structural layers

The Ursatz

The schenkerian analysis is probably mostly well-known for the idea of the *Ursatz*, a german term that translates to "fundamental phrase", which describes the structure of a tonal work as it occurs at its most lower (or "background") layer and in the most abstract form. It consists of two parts, or parallel voices:

- the *Urlinie*, or "primordial line", purely melodic, which results from filling in the spaces of the Klang;
- the *Bassbrechung*[5], or "bass arpeggiation" composed of a fundamental arpeggio whose function, despite being itself monodic, is purely harmonic.

Any piece of tonal music can be seen as an elaboration of this pattern:

- Tonal pieces generally start with I, even if often it is delayed;
- the V - I represents the perfect cadence of the piece, but in a longer piece whole sections may prolong V;
- in longer pieces, there may be other harmonic areas prolonged in between the initial I and the V of the final perfect cadence;
- the bass of the fundamental structure can appear in many different layers of a piece.

The bass line is simply an harmonic progression and so Schenker's theory seeks to understand music in terms of a two-part contrapuntal structure.

Figure 2.7: The *Ursatz*.

[5]Also named *Grundbrechung*.

Schenker suggested that this progression (along with a number of variants) was the most basic expression of tonal music.

The analytic process

Thanks to the well-defined structure of a musical composition described in Schenker's theory, the process of analysing such piece becomes very precise and algorithmic. This property represents the main reason why this approach was selected for the purposes of this thesis, as it is perfect to be adapted, coded and decomposed in a well-defined model. The analysis process can be divided into four main stages [23]:

1. Labelling foreground harmonies with Roman numerals;
2. Preparing the score for analysis and marking *Vordergrund* elaborations;
3. Identifying underlying elaborations beneath the *Vordergrund*;
4. Showing how the piece can be understood as an elaboration of one of Schenker's *Ursätze*;

The first stage consists in a harmonic analysis of the examined piece of music. This procedure allows us explore how dissonant notes, namely those not in the relevant harmony, can be shown as elaborations of consonant ones, that is those notes that are part of the relevant chords.
The first step is to determine the key of the musical piece, which in general can be done by looking to the key signature and to the last note/chord of the analysed segment. After that, it is possible to identify the different chords of the fragment and label them, using Roman numerals, based on the grade of the scale of the previously found key. Such chords could be written in particular inversions[6], based on the note of the chord which is written as the lower one, so, where necessary, it could be useful to label the figured bass too.

[6] Inversion, in music, is a rearrangement of the top-to-bottom elements of an interval, a chord, a melody, or a group of contrapuntal lines of music. To invert a chord or an interval is to rearrange its notes so that the original bottom note becomes an upper note.

Figure 2.8: Stage 1: harmonic analysis of a musical fragment.[23]

In the second stage, or "foreground analysis", notes are grouped into elaborations of the harmonies identified in stage one. With a few common exceptions, stage two is concerned with understanding how the surface of the music works. The idea is to identify linear units and harmonic units with a process called "diminution".

The score is prepared by representing each note with a stemless crotchet, that is the notehead of a quarter note, by removing the bar lines and by deleting consecutively repeated notes or phrases as appropriate.

Then, any direct elaboration of Vordergrund harmonies will be identified, with slurs and appropriate labels: arpeggiations (Arp.), linear progressions (3-prg, 4-prg etc), neighbour notes (N) and two-note arpeggiations between voices (slur). Any repeated arpeggiating pattern, such for example an Alberti bass, will be considered as simple chords. This elaborations are called by Schenker "Linear units" and will be further explored in section 2.3.2 about musical modeling of the Schenkerian blocks.

Figure 2.9: Stage 1: *Vordergrund* diminution.[23]

The third stage, which is called "Middleground analysis" deals with finding connections and linking up the music into larger spans. Just as the Vordergrund decorations identified in stage two elaborate foreground harmonies, the linear progressions and neighbour notes of this stage must also make harmonic sense. The only difference is that now such notes are elaborating larger units, in which harmonies are grouped together in specific tonal patterns, such as cadences.

This stage is not as mechanical as the other, because there can be multiple possible solution for identifying such patterns. Schenker suggests that the principles of melodic fluency becomes increasingly important at deeper layers of the musical structure, so, where possible, a good way to deal with this is to try to find simple step-wise connections between elaborations. Decisions as to which notes have to be marked as structurally more important should balance the consideration of melodic fluency with melodic and metric prominence, and middleground elaborations are most convincing when they have good contrapuntal and harmonic support. For example, middleground passing and neighbour notes should be made consonant by the bass line in the foreground.

Stems and beams are used to show and label all large-scale elaborations, while downward stems mark the roots of principal supporting harmonies in the bass. Harmonic units are marked with slurs beneath the Roman numerals and progressions from I-V with a slur that curls up and over the V.

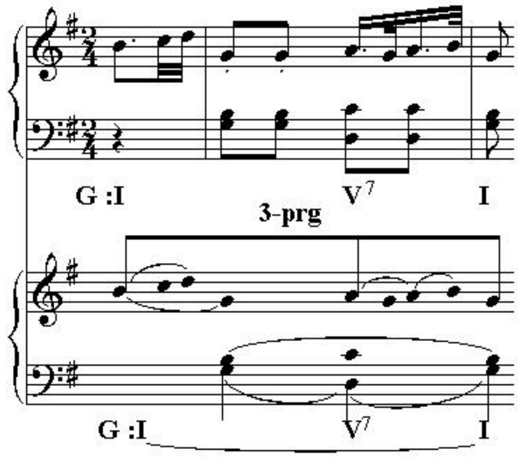

Figure 2.10: Stage 1: *Mittelgrund* reduction.[23]

Approach chords to the dominant, as for example II or IV, can be joined to V with a horizontal line; the main arpeggiations in the bass, as well as elaborations of their notes, are connected with slurs, and dotted slurs or arrows are used to show when two foreground linear units are elaborations of the same note and for register transfers. Lastly, beams, stems and diagonal lines are employed to clarify features such as unfolding and voice exchange, which involve movement between different voices.

The process of identifying elaborations beneath the surface in stage three is usually repeated several times in order to explore successively deeper layers of the musical structure.

Stage four is, in a sense, a continuation of this process, but just as we are looking for particular patterns of elaborations on the surface, Schenker proposes a standard model that can be found in various guises on the deepest level of the music, the *Hintergrund*. This consists in the identification of the *Ursatz*.

The Urlinie must descend diatonically to $\hat{1}$ by step from one of three possible *Kopftone*, or head tones: $\hat{3}$, $\hat{5}$ or $\hat{8}$, and once its scale degree, the descent can only continue down, without returning to previous scale degrees. The exception is the interruption which can only occur after $\hat{2}$ and always returns to the original Kopfton. For an Urlinie from $\hat{5}$ or $\hat{8}$ to be convincing each note of the descent must be properly supported harmonically and with counterpoint.

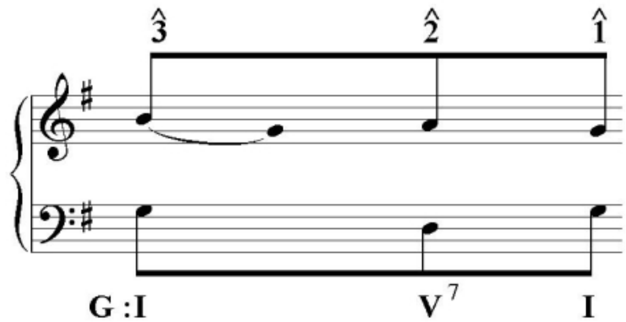

Figure 2.11: Stage 4: Finding the *Ursatz*.[23]

2.2.3 Atonal and athematic music

The credit for the spreading of atonal musical thinking at the beginning of the past century belongs to many different composers, however, it was the Viennese school of Arnold Schönberg, Alban Berg and Anton Webern (approximately in the period from 1908 to 1923) that went further than all, and most consistently, in the aspiration towards the destruction of tonality.

Trying to break away from tradition in musical expression, Schoenberg and his students gradually began to opt in their works for the aesthetics of avoiding all hitherto valid musical laws, or getting rid of them altogether. In his essay *Composition with Twelve Tones*, Schönberg writes: "The hallmark of this style is the treatment of dissonances such as consonances and the renunciation of the tonal center. As a result, the tonic is avoided and modulation is excluded, because modulation is a process that means the transition from one established tonality to another one"[1].

This process of treating dissonances as consonances has since been called the "Emancipation of the dissonance". Chords were no longer built on the principle of stacking thirds, and when even the superimposition of fourths started to be considered obsolete, other intervals were considered as consonances, and chords were built on sevenths, seconds and even tritones. In the end, the octave intervals themselves were removed.
Atonalists rejected the classical symmetrical rhythm and started complicating the rhythmic side of their works by applying irregular divisions of the notes into triplets, quintuplets etc, introducing accents on upbeats, sharp irregular rhythms underlined with double-dotted notes, frequent changes of measure between the bars, but most of all they avoided even a hint of typical used rhythms and cadences. They also renounced to the thematic principle in the construction of the work, upholding consistent athematicity.

This led to the disintegration of the forms preserved until then. The only element on which to build became the interval, and the only procedure became the principle of freely varied development, in which no motif is repeated exactly as the same, but is constantly varied. In addition, Schoenberg and his students introduced into the composition "expressive, sounding pauses", the so-called "silent tones", moments where the listener's imagination itself is the player of the music.

During the 1920s and 1930s, the Czechoslovak composer Alois Haba generalized the principles of athematic music, approximately through the following three basic rules [11]:

1. the abandonment of already known musical forms - sonatas, rondos, scherzos, fugues, canons, etc;

2. the avoidance of applying specific previously-used procedures in composing a periodic structure of melody, thematic work, repetition and transposition of motifs and the rejecting of sequential movements;

3. the understanding that the basic feature of a musical form is its abstractness, and the creation of a new realization of this notion. Consequently, the importance of thinking in new, plastic rhythms, of shaping in mutually different variants the three basic characters of the melodic movement: ascent, permanence at a height, and descent; the creation of irregularly divisible melodies.

From free atonal and athematic composition very quickly appeared the methods that led to organized atonality. In fact, while the attention was initially focused on the task of legalizing even the use of different pitches within an octave, there was an almost immediate effort to organize all other elements and parameters of music.
To strengthen the principles of atonality and to establish a set of rules that can achieve so, serialization of music was invented.The sequential organization of exclusively pitch, and by extension of only one musical parameter, is called a "serial technique". If other characteristics of notes, such as duration, intensity, instrumentation etc. or other musical parameters are included in the organization and interconnected, then we will be talking about multi-serial technique. Thus, there are qualitative differences between free atonality, serial and multi-serial techniques.

For a better understanding of how atonal music can achieve a specific order and identity, Czech composer and music theorist Ctirad Kohoutek proposed a following simple scheme [16].

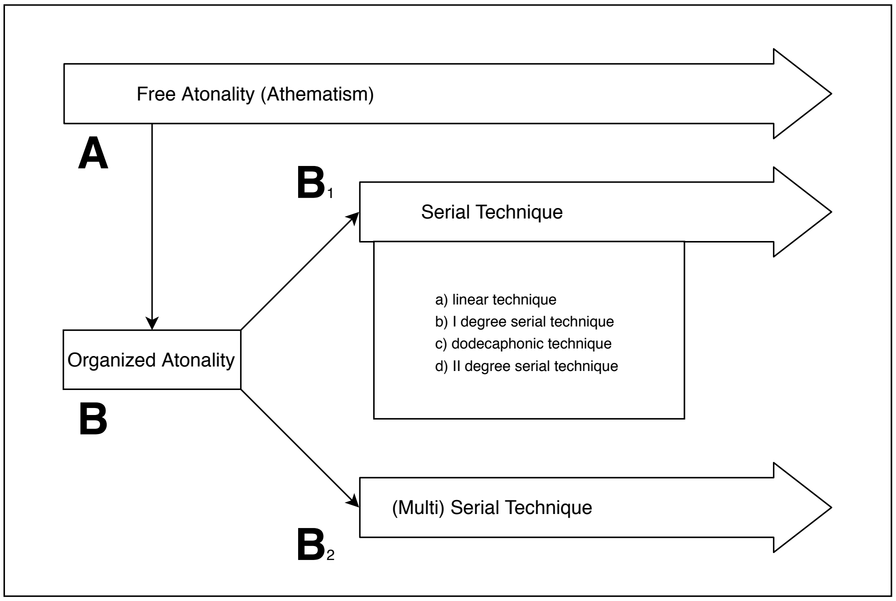

Figure 2.12: Types and phases of atonal-serial and serial technique.

The types and phases of serial technique are:

a) Linear technique, pre-dodecaphonic. The composer works with one, or, in some cases, with a few lines in a purely linear, melodic way. It is primarily a matter of arranging different notes in a specific order built with different techniques such as repetition, transposition, inversion, and sometimes augmentation or diminution, all of which are to be used alternately, without adhering to any pre-set principle;

b) First degree serial technique. A complex series, or several, of tones, from three to twelve different pitches, are used not only linearly, but also vertically, and in combination between them;

c) The dodecaphonic (twelve-tone) technique, which is, in fact, a consistent extension of the first degree serial approach to all of the twelve semitones of the chromatic scale;

d) Serial technique of II degree, post-dodecaphonic, which increasingly uses certain interval and motivic-structural relations, often even to the detriment of the already achieved dodecaphonic organization. Thus, it is mostly - at least in the dimensions of the whole composition - about the uniform application of all twelve tones, yet this way of working is based on the use of smaller groups of tones (so-called microseries) which are developed from and operated by dodecaphony.The completely free serial technique of the II degree is again very close to the atonal method of composition.

The final phase of the serial technique - intended as a broader approach which works not only with series of pitches, but also with series of durations, dynamic degrees, pauses, instrumental colors, series of metric and non-logical changes - represents the total organization of all components of the musical flow.

In the middle decades of the twentieth century, there was a growing tendency towards thematic "economy" with compositions that could be considered even "supereconomic" or "ultraconstructive", in which each phrase or figure and each inner section are derived from only a few basic motif patterns. The characteristic motif, or more often only an interval, gained basic significance for the construction of the whole composition, changing only in rhythm and expression. The predominance of the interval structure over the strict sequence of tones determined the path towards later structuralism.

2.2.4 On microtonality

Not all the existing musical languages are built on the use of the chromatic scale. There are many musical traditions, all around the world, that adopt scales subdivided in more than twelve intervals.

Although music based on the chromatic scale is the most widespread, the phenomenon of these musical languages, called "microtonal systems", is not completely unusual, nor even is it new, as it was common in antique music and still is predominant in folk music of certain regions of Asia, Africa and the Middle-East. Such musical languages, which have a larger number of pitches per octave, will use totally different melodic and harmonic rules, varying from style to style, so in this section there will be a brief presentation of what such rules could be, and how to create a coherent microtonal musical structure.

Figure 2.13: Quarter-tone "Bichromatic" scale.

Many contemporary composers have used, and still use, microtonal music for the immense range of unexplored possibility that it offers to be used for expressive and artistic purposes.

Being a field of study subject to much speculation and research, a real theory of "microtonal harmony" has never been formulated, where the term harmony has to be considered in the broad sense of "set of rules for the succession of simultaneous sounds", nor is there a universally accepted notation.

The most widespread one is probably the Skinner notation, however, with the tendency of contemporary composers to develop their own personal notation systems, to best meet their expressive needs, no one is better than the other. More developed systems are build for cases of different micro-tonal scales, where a tone is subdivided in even more microtones.

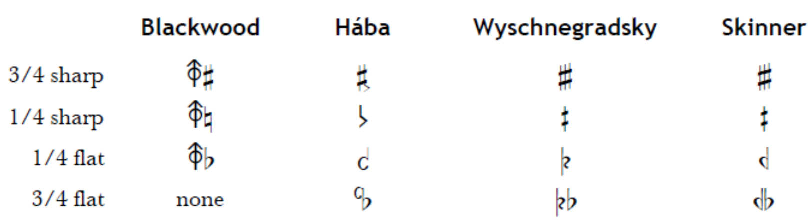

Figure 2.14: Different accidentals notations for a quarter-tone system.

In the systems based on the chromatic scale, we can identify perfect intervals, as the octave, the fourth and the fifth, and major or minor intervals, as seconds, thirds, sixths and sevenths. In a quarter-tone scale, taken as the principal example of microtonal system, the introduction of new pitches is naturally followed by the appearance of new kinds of intervals.

A minor interval will be preceeded by a "subminor" interval, which will be a quarter-tone narrower and thus will show a particularly high degree of roughness, and will be followed by a "neutral" interval, which will be placed exactly between the minor and major chord, hence the name. Similarly, the immediately following major chord will in turn be followed by a "supermajor interval".
In the same way, a perfect interval will be preceeded by a "narrow" version of itself, lowered by a quarter-tone, and will be followed by a "wide" one, raised by the same value.

Clearly such system will present a higher degree of enharmony, with many tones having multiples roles depending on the way in which they are considered, creating, consequently, a very complex set of "harmonic" rules. New chords, made up from the stacking of subminor, neutral or supermajor thids, can have a great impact on the overall sound of a musical piece, and the rules of proximity between chords have to be rewritten from scratch.

There are a lot of different musical genres that make use of specific harmonic theories in a microtonal environment, each one different from the other, and still musician are creating new musical scales, with different ratios between the intervals. Each one of these scales will potentially need a new theory and new harmonic principles, with the possibility to achieve completely new musical languages: such is the potential of exploring microtonal music.

2.3 Musical Modeling

This section is concerned with providing a quick introduction to the main compositional principles of tonal music in its more general sense, as expressed in section 2.2.1. Since a complete dissertation on these rules would require a more extensive treatment, far beyond the scope of this thesis, we will limit ourselves, in this place, to presenting only the most common principles of melodic composition and counterpoint, as the most relevant to the concept of mobile music. Furthermore, these rules must be taken as general indications, strictly dependent on the particular style of the composition created using the framework theorized in this thesis.

2.3.1 Melody and Counterpoint compositional rules

The first step to understand the rules that govern the composition of melodies and counterpoint is to define the concepts of "strict" and "free" composition and counterpoint. Strict composition and counterpoint occur when certain sets of rules are rigorously applied, with no room for interpretation or violation of pre-established rules. On the contrary, in free composition and counterpoint there is a greater freedom of exploration and inventiveness. It follows that narrow counterpoint is generally not applied outside of purely academic contexts, while narrow composition is limited to specific compositional genres, such as the aforementioned atonal serial technique, whose true freedom lies in the generation of the rule set.

What is Melody

To better explain the principles of melody composition, a brief explanation of melody itself is necessary.
Melody, term that comes from the Greek word “μελῳδία”, “melōidía”, meaning "singed or chanted poetry", is one of those concepts for which there is no univocal definition. The very notion of melody, in fact, has changed over the centuries, assuming always different forms, and yet, when we look to the different designations reported by authoritative sources, recurrent common characteristics can be observed.

The *Dictionnaire des œuvres de l'art vocal* (1992) describes melody as “A succession of musical sounds, or of musical fragments, denoting a musical phrase, or a melodic line” [18].

The *Encyclopedia Britannica* defines it as follows: "The aesthetic product of a given succession of pitches in musical time, implying rhythmically ordered movement from pitch to pitch." [6].
In the *Enciclopedia Treccani*, melody is labeled as "A succession of sounds animated by rhythm and regulated by strophic laws, so as for it to acquire proper contours and physiognomy." [24].

Generally, we can combine the previous entries in the following broader definition:

Melody is a linear and agreeable succession of musical tones that the listener perceives as a single entity.

If we look at the different aforementioned descriptions, we can observe the presence of three essential aspects of the concept of melody:

1. The fundamental structural aspect, namely that a melody is in fact a succession of musical notes

2. The constructive aspect, present in some of the definitions, namely the set of rules from which such succession of notes is built and from which features like the melodic contour or the belonging scale are derived

3. The aspect of meaningfulness, an undefined aesthetic or semiotic feature directly linked to the perception of the listener or the composer.

We now analyse these three core features, going backwards from the last one.

Meaningfulness is perhaps the vaguest and least defined, since it varies a lot regarding the contexts in which melody is written or analysed. The aesthetic aspect of a melodic piece of music is in fact directly linked to the culture and the historical period in which such tune is written, as well as many other factors that would require a musicological treatment that falls outside the scope of this thesis. However, it is necessary for this dissertation to point out that such meaning does not necessarily have to remain confined to a purely artistic and indeterminate level. There are in fact cases, all throughout musical history, but especially in contemporary literature, of melodies, or melodic fragments, that acquire significance thanks to the specific way in which they are made. This is the case, for example, of the numerous works that have been built starting from mathematical rules such as the Fibonacci sequence (from J.S. Bach, in his Goldberg Variations, to I. Xenakis, in Metastaseis' second) or the way in which

J.S. Bach and D. Shostakovich translated the syllables of his own name into a melodic motif which he used in several of his compositions (the celebrated BACH and DSCH motif). In short, in some contexts, the relevance of a prominent aesthetic aspect is overshadowed by the significance of the composer's motivation or intention, without making the melody less interesting.

The second aspect of melody's broad definition is the constructive one, which has to do with the way it is build, and even in this case the rules applied for the construction of a melody vary greatly according to the context. The strict rules of ancient monodic composition are in fact completely different to those used, for example, in classicism, which in turn are completely dissimilar to those used in the musical movements of the 20th century. Furthermore, contemporary music sees every author, if not every single musical piece, having its own personal grammar of rules for the creation (where present) of melodies. Therefore, as for the aspect of meaningfulness, there is no universal rule, but is rather the choice of rules (and the consequent use or breaking of them in an original way) that gives importance to the constructive aspect selected for the building of each melody. This category includes all the rules that characterize the specific style of the melodic line, starting from the use (or lack) of tonality, to the type of scale or temperament used, from the rhythmic properties to the rules of the general melodic contour. It is here important to note the distinction between this category and the previous one: the meaningfulness of a melody can in fact transcend the constructive aspect, since similar aesthetic attributes correspond to different structures and vice versa. So, it is possible, for example, to transpose the aforementioned signature-motifs in a different scale or in a system with a Pythagorean temperament.

Once we have eliminated the variable aspects, the one feature that remains is the only true constant of the definition of melody, that is, to be such, it must necessarily consist of a sequence of notes. In the most experimental and extreme musical contexts, from an aesthetic point of view:

Any sequence of notes that stands out on the rest of the musical elements of the composition can be technically considered "melody".

Atonal-serial composition

Atonal-serial composition belong to the category of "strict composition", as the artistic freedom is entirely placed in the formulation of the set of rules to be rigorously used in the building process. Considering melody as a "series of notes", the significance of this process lies in the "constructive" aspect and in the "meaningful" aspect of the definition of melodies, leaving out any rules of acoustic, contrapuntal or harmonic kinds that the composer does not want to insert.

An example of an approach in which importance is given to the constructive aspect of the "melodic line" is the tone row technique, an essential element of the famous dodecaphony developed by Schoenberg, which is ruled by four main postulates or preconditions:

- The row is a specific ordering of all twelve notes of the chromatic scale, without considering the octave placement;
- No note is repeated within the row;
- The row may be subjected to interval-preserving transformations—that is, it may appear in inverted, retrograde or retrograde-inverted form, in addition to its "prime" or original form.
- The row in any of its four transformations may begin on any degree of the chromatic scale.

Figure 2.15: Example of a note sequence composed with the tone row technique.

Melody composition and counterpoint

As far as tonal music in the strictest sense is concerned, therefore excluding, for simplicity, the complications deriving from the widened tonality, post-tonalism etc., we can easily identify one rule that represents the only great principle

of melodic composition, to which all the other ones refer to: the *principle of cantability*. A melody, in fact, to be efficient, even before being aesthetically pleasing, must be able to be sung, that is, it must satisfy a series of constraints imposed by the nature of the human auditory and vocal systems.
These rules, which are taken from strict counterpoint, are not however to be understood as insurmountable constraints, but rather as suggestions for the creation of melodies with the potential to be musically effective.

- By the definition of tonality and according to the rules of tonal architecture analyzed in section 2.2.2, a melody with tonal coherence is made up of one or more elaborations of the Schenkerian Ursatz. It follows that it must begin and end with the tonic or, in particular cases, with a note belonging to the tonic chord, with the exception of particular *anacruses*, which will be discussed later.

- Similarly, it must have a structure that allows the identification, net of extensions, of a perfect cadence, therefore it must necessarily include at least one note belonging to the dominant chord.

- For it to belong to the classification of "strict tonality", each note of the melody must belong to a predetermined diatonic scale, be it major or a combination of the different variations of the minor scale. The presence of chromaticisms is therefore to be excluded, as they are relevant to a more extensive vision of the concept of tonality, with different rules, but in any case derived from those presented here.

- For its whole duration, a melody should not extend, in pitch, outside an interval of tenth. This rule comes from the average *tessitura*[7] of the human voice, regardless of the vocal register. Melodies that extend beyond this extension, in fact, tend to be automatically transposed into it in the eventual case that they are sung.

- The melody must be sufficiently varied, and therefore cannot be limited to the continuous and unchanged repetition of a single section. At the same time, repetition of the same note is usually not recommended unless there is a specific harmonic need.

[7]Italian word meaning "texture" and used to identify the range of the possible playable pitches of a musical instrument.

- A good approach, but not to be rigorously observed, is the construction of melodies with a stepped trend, that is, proceeding with small intervals. The organization of the intervals deserves particular attention. In fact, dissonant intervals must be avoided, as minor seconds, excess fourths etc.

- Consecutive jumps in the same direction must necessarily identify a particular triad, while an interval wider than a perfect fourth must be followed by a movement in the opposite direction, unless there is the delineation of an open chord. For example, if the melody develops an interval of a fifth, the next note must necessarily be placed at a further fourth in the same direction or, if the interval is ascending, such note must necessarily be lower and belonging to a jump of smaller size.

- Leaps greater than a minor sixth and different from the octave, therefore those that are more difficult to sing, are generally avoided. This is due to the increasing difficulty in singing such intervals perfectly tuned, except for the more natural octave jump.

- As regards the general outline of the melody, for it to be coherent it must have a single climax, be it a *zenith* or a *nadir*, which can however be identified by one or more notes, as long as they are located in the same thematic region.

- Finally, it is necessary to make an important note on tendency tones, namely those notes of the scale that have a natural tendency to resolve to others and which, consequently, must behave in this way. This is the case of the sensible, that is the seventh degree of the scale, which resolves to the immediately higher tonic, or of the subdominant which, although on a lesser extent, resolves to the median. Generally, even the second and sixth degrees tend to resolve respectively to the tonic and on the dominant, but in this case the rule is not so rigorous.

2.3.2 Schenkerian Building Blocks

Having examined the general principles of the composition of a melody in a strictly tonal context, we will now examine how these principles are translated into the constructs that make up the Schenkerian decomposition, or *Auskomponierung*.

In section 2.2.2 it has been shown how, after a preliminary phase of harmonic analysis, takes place the procedure of diminution from the *Vordegrund* to the *Mittelgrund*, in which a series of operations are carried out, aimed at removing all those notes that can be considered "decorations", and therefore do not belong directly to the "supporting structure" of the musical piece.

Such method is derived from the concept of *prolongation*, which consists in the process through which a pitch, interval, or consonant triad is able to govern spans of music when not physically sounding. Prolongation can be thought of as a way of generating musical content through the linear elaboration of simple and basic tonal structures with progressively increasing detail and sophistication.

There are different techniques of prolongation:

- **Arpeggiation**

  Arpeggiation is the simplest form of elaboration. It prolongs a harmonic unit by arpeggiating (making into an arpeggio) the notes of the triad, and therefore delimits a tonal space for elaboration, but lacks the melodic dimension that would allow further developments. In Schenkerian analysis, diminutions generally prolong both a harmonic unit and a particular note from that unit, so the arpeggiation could be the prolongation of either its first or last note.

- **Consonant skips**

  A consonant skip contains only notes from the harmonic unit that it is prolonging. It may leap from one note of the harmonic unit to any other, so it is kind of an incomplete arpeggiation.

- ***Züge* and passing notes**

  A *Zug*, or “linear progression” is the stepwise filling of some consonant interval. The simplest linear progression is the passing note, which is dissonant as it passes from one consonant note to another. So, the most elementary linear progressions are determined by the tonal space that they elaborate: they span from the tonic to the mediant, from the mediant to the dominant or from the dominant to the octave of the triad, in ascending or descending direction.

Linear progressions, in other words, may be either third progressions (*Terzzüge*) or fourth progressions (*Quartzüge*); larger progressions, result from a combination of these, as the *Quintzug* being a succession of a *Terzzug* and a *Quartzug*. Linear progressions may be incomplete, or "deceptive" when one of their tones is replaced by another, but nevertheless suggested by the harmony. Lines covering a seventh or a ninth are called "illusory", considering that they stand for a second with a register transfer: they do not fill a tonal space, they pass from one chord to another.

- ***Nebennoten***

  Nebennoten, or "neighbour notes", are related to the concept of passing note and are sometimes referred to generically as "adjacencies". Whereas the passing motion progresses from one consonant note of the harmonic unit to another, the neighbour note returns to the initial note.

  Neighbour notes can prolong either the first, third or fifth degree of a triad and they must be no more distant than a major second away from the note being prolonged, hence the name. Neighbour notes can also be incomplete, appearing either before or after the consonant note.

- **Combinations**

  Almost all tonal music can be understood as in terms of the previous four basic linear units, and many figures that initially seem more complicated are often made up of a combination of one with another. If for example each note of an arpeggiation of a C major chord is decorated by a secondary linear unit in which each note constitute an upper neighbour note of the previous one, this figure will be called *Übergreifen*, meaning "overlapping", "reaching-over". If the neighbour notes, or passing notes, are lower than the main ones, we would be talking of *Untergreifen*, "reaching-under"

- ***Ausfaltung***

  Ausfaltung, or "unfolding", is an elaboration by which several voices of a chord or of a succession of chords are combined in one single line so that two different melodic voices can be intertwined by alternating the presence of a note or group of notes taken from the first one and another one taken from the second one. The result is a combination of the to melodic lines in a single one.

- **Register transfer and coupling**

  Register transfer is the motion of one or several voices into a different octave. For the rules of melodic composition analysed in section 2.3.1, music normally unfolds in one register, which Schenker calls the *Obligate Lage*, but at times melodies can be displaced to higher or lower registers. These events are called, respectively, *Höherlegung*, or "ascending register transfer" and *Tieferlegung*, or "descending register transfer".
  Coupling happens when the transferred parts retain a link with their original register. The melody, in this case, appears to unfold in parallel in two registers.

Further kinds of elaborations are applied to the *Ursatz*, but here will be listed only the ones that are most relevant for the purposes of this thesis.

- **Anacrusis**

  The *Kopftone* of the *Urlinie* may be reached only after an ascending motion, either an initial ascending line, called *Anstieg*, or an initial arpeggiation, which can even be longer than the descending fundamental line itself, resulting in melodies in arch form. So, anacruses are to be considered as elaborations of the fundamental structure themselves.

- ***Unterbrechung***

  The Unterbrechung, or "interruption" is an elaboration of the *Urlinie*, which can be interrupted at its last passing note, scale degree $\hat{2}$, before it reaches its goal. As a result, the *Bassbrechung* itself is also interrupted on V. Both the fundamental line and the bass arpeggiation are bound to return to their starting point and the fundamental structure repeats itself, eventually reaching its goal. The interruption is the main elaboration that generates the musical form of the piece.

- **Transference of the fundamental structure**

  The forms of the fundamental structure may be repeated at any level of the work. That is to say that any phrase in a musical piece, or self-coherent fragment of it, could take the form of a complete fundamental structure. Many classical themes form self-contained structure of this type. This resemblance of local middleground structures to background structures is what gives Schenkerian analysis the appearance of a recursive construction.

All the rules of tonal melodic composition treated in this chapter, as well as the reduction rules of Schenkerian Analysis, constitute the core of the systematic composition of melodies with constructive coherence. These rules, specially reworked and organized, can therefore be applied to create an algorithmic composition of melodic elements starting from given musical material.

Chapter 3

Cellular Modeling of Music

Once we have introduced the most important compositional principles, the rules of tonal, atonal and microtonal music and the foundations of the theory of Schenkerian analysis, we proceed with the presentation of the principles of Cellular Music, explaining the methods and ways in which it is possible to create music inspired by the life, evolution and interaction of cells in a Petri dish. The set of principles presented in this and the next chapter are defined in a musical framework, that is a compositional paradigm that represents a novel musical model that can be applied for the creation of original compositions.

3.1 On the concept of Melodic Cells

This section briefly illustrates the theoretical foundations necessary for a complete and cohesive treatment of the theory of Cellular Music. The concepts presented here may seem trivial at first glance, yet for them there is often no universally accepted definition. Therefore, this chapter also takes on the task of defining a coherent nomenclature that can be used in the rest of the dissertation to avoid confusion and better explain concepts that might otherwise seem nebulous.

3.1.1 A brief description of Notes

In all of this, the "note" is identified as the atomic component of the definition of melody. Even if it may seem trivial, it is necessary to clarify, at this point, what are the essential characteristics of a note, in order to understand how they intervene in the construction of melodies and, therefore, how they can be related to each other.

In the context of this thesis, the term "note" will be used in the most general definition of "representation of a sound", both in a notational context, be it written or coded, and in an acoustic one. To avoid situations of confusion, the term "note" will also be used as a synonym for the term "musical tone", while the latter will be associated exclusively with the definition of major second interval, fundamental element of any diatonic architecture.

As it is known from basic music theory, a note is made up of four main features:

- **Pitch**, namely the perceptual property that allows their ordering on a frequency-related scale
- **Duration**, the amount of time the note lasts, often as a multiple of a fixed quantity called "Tatum"
- **Intensity**, or Loudness, that attribute of auditory sensation in terms of which sounds can be ordered on a scale extending from quiet to loud, namely the perception of sound pressure
- **Timbre**, or Tone Colour, is the perceived sound quality of the note.

Of these four characteristics, the first three are undoubtedly the most important, for the purpose of melody building. More precisely, the combination of several notes causes their respective pitches to identify a general outline for the melody, while the succession of their individual durations defines the rhythmic aspect. Thus, the combination of these two qualities, to which various construction rules are applied, in certain compositional contexts, constitutes the most general definition of melody mentioned above. Lastly, the variation of intensities throughout the melodic line grants a sense of continuity to the tune.

Let us set aside the timbral aspect for now, since it can be considered secondary to the others, as regards the more general definition. A musical note, in fact, can be considered as such regardless of the tone colour, which assumes relevance exclusively in the acoustic plane.

More elaborate musical attributes can be seen as deriving from simple rules imposed exclusively as constraints on the succession of pitches and durations of the various notes within a melody. For example, the presence of a specific musical metric, intended as a periodic recurrence, not necessarily explicit, of accenting elements within a melody, can be considered as a rule on the succession of durations (which must be multiple of the tatum and arrayed in a certain way) and on the intensity of the notes positioned at regular time intervals.

Similarly, whether or not the melody belongs to a specific tonal scale, can be represented as a constraint on the possible pitches of the notes that make it up, and so on.

3.1.2 Melodic cells, Figures and Motifs

A fully-fledged melody can consist of a very large number of notes, but this is not always the case. We will denote with the generic term "micromelody" a melody consisting of a limited number of notes, usually comprised between an absolute minimum of two, since a single note cannot satisfy the definition of "succession", and a variable maximum, often dependent on the metric.

A structure of this nature can have several roles within a musical piece, each identified by a different term.

In the 1957 *Encyclopédie Larousse*, a cell in music is defined as a "small rhythmic and melodic design that can be isolated or can make up one part of a thematic context". The *Encyclopédie Fasquelle* also defines a cell as “the smallest indivisible melodic unit”. J. J. Nattiez, in his *Musicologie générale et sémiologue*, states that “a cell can be developed, independent of its context, as a melodic fragment, it can be used as a developmental motif. It can be the source for the whole structure of the work, in which case it is called a generative cell”[22].

On the other hand, a motif, or motive, is a short musical phrase, representing a salient recurring figure, musical fragment or succession of notes that has some special importance in – or is characteristic of – a composition: the aforementioned Encyclopédie Fasquelle claims that it may contain one or more cells, though it remains the smallest analysable element or phrase within a subject.

Lastly, a figure, also called figuration, has a similar definition to the one of a cell, being a small succession of notes, however, the substantial difference lies in the fact that while a cell, and by extension a motif, resides in the so-called *Hauptstimme*, that is the primary voice, or the often melodic foreground of a piece of music, the figure is displaced rather in the *Nebenstimme*, that is a secondary plane, part of the musical background, giving a certain degree of motion to the composition, but without having the prominence of a melodic or contrapuntal phrase.

3.1.3 Composing with micromelodies

Throughout the history of music as we know it, starting from the Middle Ages, the possibility of building melodic themes starting from certain motifs or specific melodic cells has often been exploited. Among the most ancient examples, the most famous case is the motif of the “Dies Irae”, consisting of 8 notes at intervals of descending thirds, used in several compositions up to the present day. In this case, the motif consists of a single melodic cell that occurs several times within the same theme.

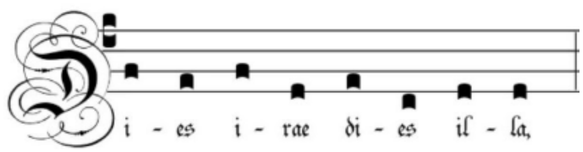

Figure 3.1: The "Diaes Irae" motif

The explicit use of melodic cells as a constructive block of entire pieces becomes common practice in Renaissance music, where the compositional technique of imitative counterpoint exploits precisely the appearance, often repeated, of clusters of cells which, repeating themselves in different contexts, often create a polyphony very articulated while remaining constantly recognizable. This technique was subsequently developed during the Baroque period, where it is often single cells (or, to be precise, unicellular motifs) that are repeated and developed in the art of fugue. With classicism first, and especially with the subsequent romantic period, entire compositions, structured on the presence of motifs and representational musical cells, were born. R. Wagner himself, considered one of the greatest users of the leitmotiv, often employs unicellular motifs, such as the theme for Fafnir in his Siegfried or the theme for the magical casket in Tristan und Isolde.

Finally, with the advent of contemporary music, compositions consisting of the deep exploration of single micromelodies or rhythmic cells have become increasingly frequent, so much so that they actually dominate some entire compositional currents. This is the case, for example, of minimalist music, which often consists of the presentation and gradual evolution of a single musical cell. The very first composition to be considered as belonging to the genre of minimalism, "in C" by T. Riley, is an extremely relevant example, because it consists almost exclusively of melodic cells which, by being played in a semi-aleatoric way, generate a very interesting piece, of countless possibilities.

Figure 3.2: Terry Reilly's "In C.", the first minimalist piece ever written. It should be noted how it is divided in small often unicellular motifs.

Obviously, the secret lies in delineating well-defined and developed sets of rules. The spawning of a chaotic environment can only be avoided by carefully controlling the overlap and the juxtaposition of the cells that are inserted into the piece.

Even though these rules can, in theory, be free and at the discretion of the composer, in practice they depend on the stylistic context in which one decides to displace the piece of music. A perfectly tonal system will therefore have very different constraints compared to a microtonal or completely atonal system.

3.2 The Musical Habitat

Although this is not always true, it can be said that a simple melody, or a fragment of it, is not sufficient to constitute an object that can be defined as "a piece of music". To do this, it is rather necessary a more extensive environment, which allows us to relate multiple cells or melodies, thus giving the sense of unity that, when applied to simple ordered sounds, we call "music".

This environment can take on different forms and meanings based on various factors: in the case of tonal music, it is identified with harmony, understood precisely as that particular set of musical rules that allow the combination of single musical elements first in chords and subsequently in chord sequences or progressions. In the case of atonal music this rule becomes more abstract, dependent on factors not so immediately intuitive, but still existing, since, otherwise, an atonal piece would risk appearing as a pure fruit of chaos.

3.2.1 Rules of Drone Music

In the case of drone music, a musical genre derived in the 60s from minimalism, such set of rules is simplified in the creation of "drones", also called "bourdons", namely harmonic or monophonic accompanying effects in which a note or a chord is played continuously for a substantial part or for the whole composition, sustained or repeated. Acoustic examples of this effect are the typical sound of bagpipes or hurdy-gurdies, and the folk songs often written for such instruments. Everything that happens in the higher planes of this *Nebenstimme* must therefore be in constant relationship with it, in order to ensure proper cohesion to the composition. In the case of more complicated drones that change during the course of the piece, thus identifying "harmonic sections", the term "pad" is used.

The very concept of monophonic drone plays an essential role in the definition of cellular music as presented in this thesis, since the presence of a single fundamental note, or of a group of notes individually considered, allows each melodic cell inserted in the composition to be related to it.

3.2.2 The timbral plane

In section 3.1.2 we have dealt with the creation of melodic cells and, by extension, the creation of melodic segments of varying length, as separate and characterizing elements of the whole melodic theory, which can be considered to be derived from them. However, in exemplifying the concept, the timbral aspect of the definition of note as a constituent element of a cell was temporarily set aside.

Let us now suppose to have a two-dimensional space limited to the ends, like a sort of canvas, which represents the environment described above, in which to insert an isolated melodic cell and to which a set of rules can be applied. If the aspects of pitch, duration and intensity are included within the cell itself, it is also possible to assign to it a particular timbre, which depends on the position of the cell at the moment in which it is observed, in order to complete the definition of "note" and, by extension, that of "melodic cell". The two-dimensional space thus becomes a sort of *timbral space*, in which the objects arranged within it are uniquely assigned a timbre, based on the position they assume.

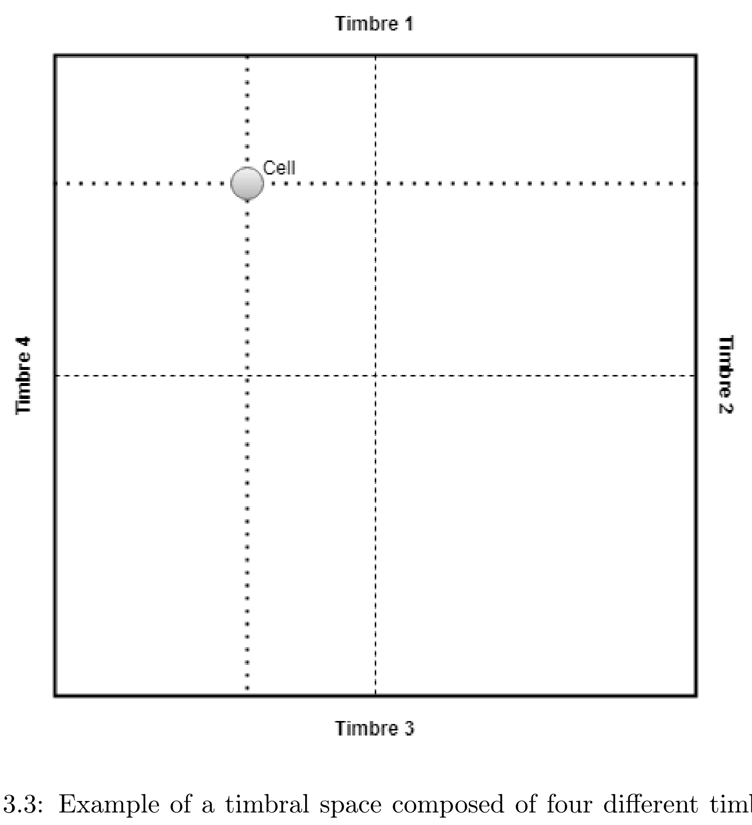

Figure 3.3: Example of a timbral space composed of four different timbres on the edges.

For example, if four different timbres are arranged on the four ends of the limited plane, the sum of the relative distances from each of them can identify, for the cell placed therein, a unique tone colour, given by the weighted mixture of the four "pure" timbres placed on the boundaries of the space.

In Figure 3.3, the cell is placed at a distance of 2/10 between the ends of timbre 1 and of the timbre 3, and at a distance of 3/10 between timbre 4 and timbre 2. It follows that the tone colour of the cell will consist of 40% of timbre 1, 35% of timbre 4, 15% of timbre 2 and 10% of timbre 3.

3.2.3 A musical pad as a *habitat* for musical cells

Once the two-dimensional timbral space has been defined, it is possible to add a third dimension to the environment by linking the drone concept presented in section 3.2.1 to it.

If we divide the plane into regions, which may or may not be regular, and assign a particular drone to each of them, identified by a single bass note, it is possible to create real habitats in which melodic cells can be inserted and with which they can relate.

A melodic cell arranged in a certain area will therefore be able to generate a primitive example of drone music, where the habitat identification note will represent the drone.

Now, suppose we give the cell the ability to move within the timbral space, while remaining within the same habitat. Since the timbre at each instant will depend on the position of the cell, it will be possible to perceive a variation in the *colour* of the music, which in this way will create an acoustic feedback of the motion of the system. If this cellular motion were to be calculated and determined by the state of the cell at each instant and by a value that would put this state in relation to the habitat in which it is located, it would be possible to make it autonomous, and the system would not be dissimilar from a sort of “musical Petri dish”, whose drone-areas would represent a kind of *culture medium* for *cellular musical organisms*.

If the motion of a cell were to lead it to a different area of the plane, identified by a different bass note, the acoustic effect would be that of a drone change.

In the case of several cells present at the same time within the plane, if the habitats in which they are located are different from each other, the simultaneous activation of more drones can occur, which would therefore create a sort of "harmonic pad" as background of the acoustic product. The constant motion of the cells in space, which will be studied in depth in the following chapters, will therefore give a certain dynamism to the produced music, since the different combinations of drones can identify different chords, in a context of tonal music, or different clusters, in the case of atonal music.

It follows that the choice of the bass notes that can be assigned to such habitats, as well as their relative position within the bidimensional space, cannot be random, but must be carefully considered.

3.2.4 A brief excursus on structural harmony

To better understand how to choose the combination of different bass notes for habitats, as well as their position in the plane, in a tonal context, a quick smattering of the theory of structural harmony, conceived by A. Schönberg in the 1940s, is necessary.

In his treatise "Structural Functions of Harmony"[30], Schönberg theorizes a way to schematize the proximity or distance of different chords from that of the tonic of a specific key. He calls this table "Chart of the Regions", a setting that allows a better understanding of the unity of harmony of a piece of music. As reported in the treaty:

> *The concept of region is a logical consequence of the principle of monotonality, according to which every digression from the tonic is always to be considered in the context of the basic key to a relationship that can be deemed direct or indirect, near or far. In other words: in a piece of music there is only one key, and each part of it that was once considered as a different tonality is only a region, a harmonic contrast within the same key.*

In the table, the regions are arranged so as to indicate the degree of affinity with respect to the tonic chord, which occupies the central position. The further a chord is from the root, the more it can be considered harmonically distant from it. It is not random, therefore, that much of tonal music (in the strict sense) tends to limit itself to using chords very close to the tonic, to maintain a certain sense of identifiability in the definition.

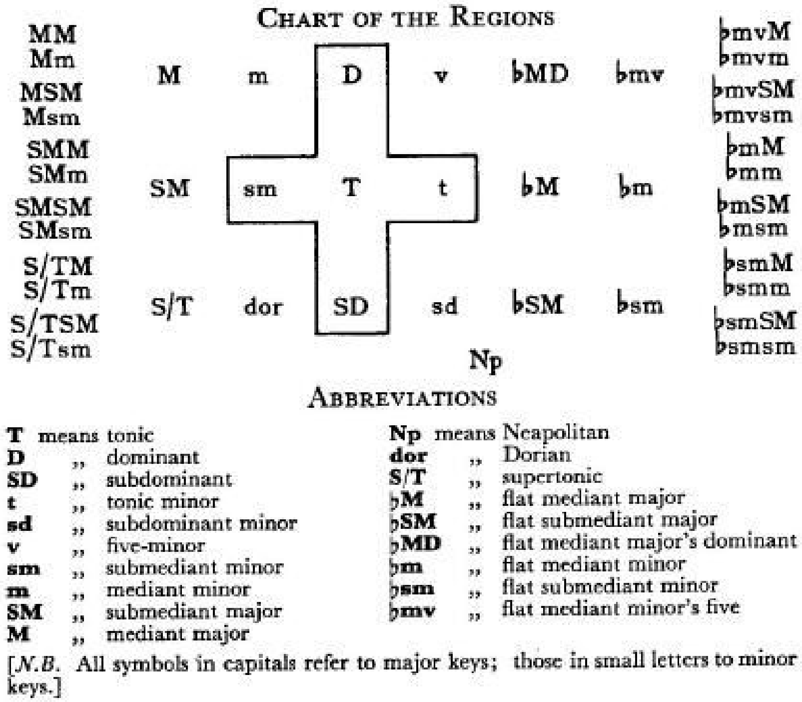

Figure 3.4: Schönberg's Chart of the Regions, with the abbreviation legend.

3.2.5 Principles of habitat displacement

While there could be no strict rules to how to choose and displace habitats in the acoustic plane, in this section there will be some examples of how the combination of different drone-areas can be performed.

The simplest case of all, albeit limited in the overall produced effect, is that of drones that, played together, identify a simple chord. This expedient can be valid if one wishes to create a very simple piece, limited to the tonic chord of the chosen tonality, since any possible combination of notes belonging to this chord would uniquely identify it.

If one wanted to embrace tonality in its strictest sense, the decision would be more complicated. The optimal solution can be directly extracted from the analysis of the table of regions, as presented in the previous section. In fact, supposing one wants to create a *monotonal* piece, in the expanded meaning defined by Schönberg, i.e. in which each modulation must lead to a region as close as possible to the tonic, the optimal solution is only one: the choice of drones falls on the notes belonging to the regions adjacent to the tonic.

In the case of four habitats, for example, the optimal choice would fall on the tonic degree, the subdominant, the dominant and the submediant. In fact, these are the closest chords, except for the tonic itself, whose presence is unquestionable. It is thus possible to observe that, assuming the presence of multiple cells in the environment, except for the case in which all the habitats are active simultaneously, it is always possible to identify, in the concurrent execution of more drones, a specific chord, belonging to one of the regions adjacent to the tonic.

Combination	Chord
T	T
S	S
D	D
M	M
TS	S
TD	T
TM	M
SD	S
DM	D
SM	S
TSD	T
TDM	T
SDM	S

T : Tonic Chord
S: Subdominant Chord
D: Dominant Chord
M: Minor relative Chord

Figure 3.5: Recognized chords in a tonal drone cluster based on proximal harmonic regions

More complex musical contexts require greater attention in order not to fall into banality or excessive stillness. In the case of atonal music, a possible way is to set the identification notes of the drones so that they are part of a specific cluster, be it chromatic or diatonic. Particular attention must be paid to the spatialization of said drones, whose arrangement at wide intervals can greatly help the dynamism of the composition. This concept of clustering can also be extended to musical styles further away from the western ones, making it particularly convenient, for example in the case of microtonal music.

In any case, the choice and arrangement of the habitats are at the discretion of the composer, who can thus freely express the desired musical language. When the number of areas exceeds their possibility of being adjacent, in fact, the need arises to plan the displacement of these habitats more accurately, since the cells, having the possibility of moving to neighbouring habitats, can create interesting "harmonic changes", in a broad sense, based on their relative position in the plane.

There are no particular constraints on the number of habitats that may be present, other than those of common sense: the degree of possible chaos of the final effect depends on both the quantity and quality of the habitats and the amount of cells present in them. But, after all, such are the constraints of drone music composition itself.

3.3 Lifecycle of a musical cell

Once the fundamental elements of the system have been defined, it is necessary to establish the rules that govern them and which ensure that, by combining them, a complete piece of music of full meaning can be produced. The approach used is to model these rules by taking inspiration from the behavior of unicellular microorganisms in a Petri dish, thus having elementary musical corpuscles that interact with the surrounding environment and with each other, moving throughout the acoustic space and evolving into more complex structures. This section will therefore describe the different ways in which each individual cell behaves, if isolated within the system.
It will therefore be provided with a complete life cycle which will start from its birth, will be governed by evolutionary and interactive events and will finally end with the inevitable cell death.

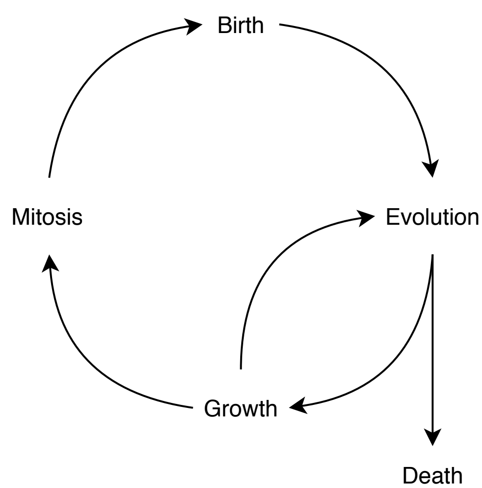

Figure 3.6: Lifecycle of a melodic cell.

3.3.1 Birth of a melodic cell

Let's define Cell birth as the event in which a new cell appears in an environment. The way in which it is inserted into the system is relevant for determining the re-

lationship between automation and user control. In fact, if, in a musical system inspired by the biological mechanics of microorganisms in a culture medium, a relevant part of the cellular behaviors has to be completely autonomous, to ensure that this structure grants melodic meaningfulness to the music from a compositional point of view, it is fundamental to allow human intervention, as far as it is possible to limit it.
For this reason, several methods in witch to have cell birth can be defined.

In this thesis, four possible cell birth procedure will be presented, as conceptual principles:

- **Direct composition** The maximum degree of artistic freedom for the user is achieved through the process of direct composition , in which a composer can manually create one or more individual cells and insert them into the ecosystem in the desired position. Of course, this practice will be subject to the previously established constraints regarding the construction of the cells, namely the minimum and maximum number of notes, the minimum duration of a note, whether or not it belongs to a specific scale or tempered system, etc.

- **Automated composition** At the opposite extreme as regards the interactive possibility, there is the spontaneous generation of new cells, which can be obtained with different methods based on the desired context. In the case of tonal music, for example, valid ways could be the use of algorithmic composition systems, naturally governed by a specific set of rules dependent on the stylistic context, or the use of artificial neural networks. The latter, in particular, especially in the case of a specific choice of style, can be previously trained to general a specific type of micromelody. Melodic cells generated with these methods can subsequently be introduced into the system in positions that could be random or determined by the presence of other micromelodies.

- **Computer Assisted Composition** A valid middle ground can be to use automated systems equipped with an interactive component. For example, Deep Interactive Evolution is a way of using a genetic algorithm that can be applied to allow the user, starting from a set of autonomously generated melodic cells, to choose, for a certain number of times, the ones he likes most, and then generates new ones starting from the latter, up to the selection of a preferred final cell. This cell, therefore, arises from the perfect union between the pseudo-randomness of automatic generation and the artistic taste of the composer who controls the system.

- ***Mitosis*** Last but not least, a further case in which the birth of a new cell can occur, although already embedded within the system, is when *cell mitosis* occurs, that is the splitting of a melodic cell, under certain conditions, in two different new cells produced by the "Genetic material" of the parent cell, therefore containing respectively a part of the parent's notes. In this case there is no way for the composer to control the displacement of the newly divided cells, that will be created in the position of the late parent and will consequently move away from each other.

3.3.2 Relating habitats and cells

Let us consider the case of a single isolated cell placed in the system, in a particular habitat. As already mentioned in section 3.2, each cell has its own independent motion, which allows it to vary its own sound properties, as well as the particular background note played. However, this motion is not accidental, but closely linked to the state of the cell at each specific instant. In fact, when a cell first comes into contact with a drone-region, it performs a quick assessment of its fitness in that particular habitat. This fitness, which may vary in different contexts depending on the style or the specific choices of the user, identifies the degree of adaptability of the cell, or how much this micromelody, in the specific moment considered, conforms to the habitat in which it is located.

For example, in a general musical context, this fitness function can be calculated as follows.

According to western music theory, each note in a diatonic scale, therefore in which the octave interval is divided into twelve sounds, can be related to a second one, identifying a specific interval. These intervals, which for convenience can be considered "compressed" to similar notes within a single octave, may be consonant or dissonant based on the distance between the notes, in variable amounts.

Although, as described in section 2.2.3, in the case of an atonal context there is a broader view of the concept of consonance, according to that principle which has been identified with the name of "emancipation of dissonance", and despite the fact that in the case of microtonality there are even more particular rules regarding the treatment of this topic, in the case of tonal music, the concept is well established.

The graph in figure 3.7 represents the "amount of dissonance" perceived by the listeners, of the various possible intervals of the chromatic scale, in the case of equal temperament[1].

This consonance index can then be used to calculate the amount of consonance between the pitch of each note of the examined cell and the one that identifies the habitat, compressing the interval within the limits of a single octave.

Once all the degrees of consonance have been identified, the average of these values can be considered a significant measure of the cell's adaptability to the particular habitat.

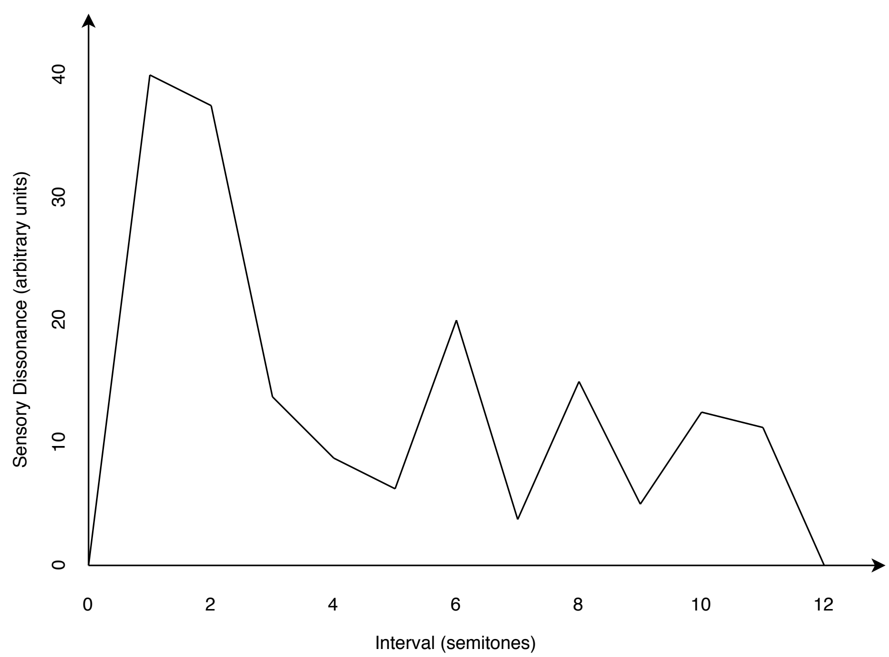

Figure 3.7: Perceptual amount of dissonance of the chromatic intervals.

Of course, in this calculation it will be necessary to introduce additional variables in the case of more specific contexts. For example, in tonal music a

[1]From Vassilakis, P.N. (2001). *Perceptual and physical properties of amplitude fluctuation and their musical significance.* Doctoral dissertation. University of California, Los Angeles.

further constraint is necessary. In fact, once the general tonality of the piece and therefore the particular habitats have been defined, as described previously in section 2.5, it is necessary to define the degree of consonance not only between the notes of the considered cell and its current habitat, but also that between these notes and the general key of the piece. In fact, a note can have a high degree of consonance with respect to the bass note of its drone, but be dissonant with respect to the tonic of the key of the song, and thus generating, in fact, a lower fitness which, without this constraint, cannot be calculated correctly, incurring in the risk of causing musical errors in the final effect. Consequently, it is necessary to further weigh the consonance values assigned to the fitness calculation.

It is important to note here that the evaluation by degree of consonance is not necessarily the only possible way to calculate a fitness value for a given cell. The belonging of a piece to a particular musical scale could be modeled, for example, by comparing the values of the notes with those belonging to that scale, discarding those outside it or assigning them a lower fitness value. This principle can be further extended and applied to define the belonging of a piece to a particular musical grammar established by the composer.

In any case, once this value has been calculated, the cell will take its own motion and will begin to vary its position within the system. The speed of this movement will depend on the fitness value, calculated at each moment: a higher degree of adaptation will correspond to a slower movement, while a lower fitness will correspond to acceleration.

In this way we want to model the realistic behavior of a microorganism inserted in different culture environments. In fact, were the habitat in which it is placed not suitable for its development and survival, the bacterium would seek a more congenial environment, tending to abandon the previous one before the end of its life cycle. This process of constant search for a better habitat reflects the tendency of tonal music, also applicable to different contexts, to always seek resolution in a cadential form.

3.3.3 Cellular Evolution

The calculation of the fitness function with the habitat is not limited exclusively to influencing the motion of the cell in question, but has more extensive effects that regulate its entire life cycle.

Starting from the moment of its birth, a new cell will never present itself to the ear of a listener twice in the same way. In fact, each cell is subject to constant evolution, which regulates its life cycle and allows it to adapt to the surrounding environment.

At regular time intervals, close enough to each other not to negatively affect the general balancing process of the system, the cell carries out a fitness assessment and, if this fitness is sufficiently high, it evolves, modifying a single note in order to have, at the next calculation, a better adaptation to the habitat in which it is located.
This modification can affect one or all the constructive elements of the note considered, namely pitch, duration and amplitude, according to the specifications defined by the composer of the piece. In a musical style that makes use of the chromatic scale, for example, the pitch of a note can be made to vary by a semitone, or, if there is the tonal constraint of belonging to a certain scale, the increase can reach the next degree. Clearly, from the point of view of melodic meaningfulness, the increase is much more representative of the concept of evolution as much as it is small, although this constraint is not rigorous.

In a strictly tonal system, based on the melody construction techniques that it has been decided to follow, this evolution may require a further level of control, to ensure that there is a certain degree of melodic "coherence" even in the individual cells, following the principles of Schenkerian analysis in which each melody and each of its sub-segments, for it to be considered coherently melodic, must comply with the principles of the *Ursatz*. In the case of a cell that has just been inserted into the system, this condition may not necessarily be immediately verified, either due to automatic creation or to a specific choice of the composer. It may therefore be necessary that the evolution is also addressed to the generation or maintenance of this constraint.

Occasionally, by mirroring the evolutionary processes present in nature, mutations may occur that can further improve this adaptation. Such mutations can be of a variable nature, however having a great impact on the long-term evolutionary process. At the same time, in the presence of very high fitness, it is possible that the cell is subject to growth, which manifests itself with the addition, at the head or tail, of a new note, which will consequently increase the genetic material. The addition of a new note, as well as the entity of its values, can be performed randomly or according to specific principles established by the composer, and must precede the evolutionary phase of the cell to obtain a better balance between novelty and adaptation to the existing material.

In fact, in a static environment, as is the case with predefined habitats unable to change over time, an evolutionary process tending to improve performance would lead the system, sooner or later, to an inevitable state of rest, that is where the cells will be adapted to the ecosystem so much that they no longer need to look for a better accommodation, considerably slowing down their motion. For this reason it is necessary to make use of a system that combines in the best possible way the deterministic aspect of constant cellular progress, which tends to optimize the conditions, with a more casual aspect, given by the unpredictability of the result of a transformation subject to mutation.

Therefore, this evolution can be modeled in the most complete and relevant way through the implementation of a genetic algorithm, so as to balance the tendency to stagnate.

The growth of a cell, which can occur, with relatively low probability, exclusively in the case of extremely favorable conditions, introduces a further possibility of disturbing the order that the system tries to obtain. In fact, the new note may not be strictly related to the previous ones, potentially causing the value of fitness to vary, even considerably.

3.3.4 Mitosis

If the cell, grown a certain number of times, reaches the size for which, by definition, it can no longer be defined as such, it incurs the process of cellular mitosis, which happens when the mother cell splits into two younger children, having the same genetic heritage of the parent.

There are several methods in which such fission can be achieved.
The simpler alternative is to split the cell by separating the two halves. This method has the advantage of producing two daughter cells that are very recognizable by the ear of a listener, since they maintain all the constructive and evolutionary characteristics of the mother cell, assuming however a life of their own and therefore starting two independent life cycles.

A different method, which leaves more possibilities for the variability of the piece, is that of the recombination of the genetic material, that is the separation of the mother cell into the single notes that constitute it, and the subsequent combination of the same into two daughter cells, according to the canons of melodic synthesis, which we will discuss later in this thesis. This second alternative offers greater possibilities of obtaining cells that are immediately significant from the melodic point of view, in the face of a lower musical consistency and a more articulated practical realization.

3.3.5 Apoptosis

As for any living being, whether or not it is a microorganism, with which one can make a comparison, death is part of the life cycle for a cellular musical organism.

In the context of a self-consistent musical composition, a fortiori, a mechanism is needed that can cleanse the cells that have completed their cycle and have therefore stopped making a significant contribution to the piece. Moreover, this mechanism is fundamental to avoid an excessive overpopulation of melodic material in the habitats. In the case of apoptosis, or cell death, the cell in question is permanently removed from the environment and eliminated.

When creating a cell, it will be assigned a particular average lifespan, the duration of which can be at the composer's discretion. This lifespan represents the time that a cell has available to evolve and interact with the others, assuming that it is in a habitat with respect to which it has an average fitness.
The permanence of the cell in habitats to which it shows a greater degree of adaptation increases its lifespan, pushing away the moment of cell death by decelerating the speed of decay, while the persistence in an unsuitable habitat will cause a progressive shortening of the life span, leading more quickly to the end.

In the next section the ways in which two cells can interact with each other will be dealt with in detail, however, in order to describe the end of the life cycle of a cell, it is necessary to premise the fact that these interactions do not always occur, but rather they are subject to the fulfillment of specific conditions, not always achievable.
It therefore follows that the cells that will meet apoptosis will be those that for the entire duration of their lifecycle have maintained a relatively low fitness function or that, even if not, have never had the opportunity to positively interact with other cells. In this way it is possible to remove from the system all those cells which, from both a constructive and a meaninful point of view, are out of place with respect to the totality of the musical environment.

Should a cell undergo mitosis, the two daughter cells would have a lifecycle reset, as they would not be dissimilar to two new cells just inserted into the system.

3.4 Cellular Interaction

After analyzing the behavior of an isolated musical cell within the acoustic space, the interaction of this cell with other cells introduced into the same system will be analyzed. It is precisely the interaction, in fact, that allows the otherwise disjoint elements to form a single musical whole and that therefore gives a complete form to the composition.

3.4.1 Reciprocal Fitness Function

Let us suppose that a cell is in close proximity to a second cell. Just as it happens between each of them and their respective habitat, the cells will perform an affinity assessment between them, to verify the satisfaction of certain constraints that define how similar they are to each other. This procedure is called "mutual fitness" and can be done in different ways depending on the context.

The melodic fitness

A possible approach is to make a note-by-note assessment, evaluating their mutual similarity, marking it according to a principle previously established by the composer, and finally calculating an average value between the fitnesses of the respective notes. A possible implementation of this method is the application of the same fitness function employed for consonances and dissonances, presented in the previous section on the relationship between habitat and cell, with the difference that in the case of reciprocal fitness, it must be calculated between two notes, each belonging to a different cell.
Calculating such value between a note of the first cell and each note of the second one, and computing the mean value of the numbers obtained, the average consonance of that note with the whole next cell will be obtained. Proceeding in this way for all the notes of the cell and finally calculating a total average, it is possible to determine a mean degree of consonance between the two examined cells, which will represent their reciprocal fitness function.
This method is very simple and easy to implement and is very convenient, especially in the tonal and microtonal field. The degrees of consonance can in fact be modified to adapt them to the particular desired context, thus conforming the cells to specific constraints and requirements.

The reciprocal fitness by interval consonance, however, may not be sufficient to describe more complex situations, such as a tonal context with more rigorous rules, where it is necessary to add an additional layer of control to evaluate the compatibility of two cells. In fact, if we wish to use the two cells for the construction of a coherent melody from the theoretical point of view, according to the rules analyzed in the chapter on musical modeling, it will be necessary to verify that both cells satisfy the requirements for the creation of such melody, requiring a series of more complex reasonings and a more articulated application. This topic will be discussed in chapter 4.

The rhythmical fitness

The pitch-based reciprocal fitness may be sufficient in some contexts, especially in the case of musical genres in which no particular importance is given to the duration ratios of successive notes or where such ratios are negligible. However, such an approach may not be enough to correctly describe the relationships between two cells in the most general sense. Two micromelodies, in fact, could be perfectly compatible if assessed with the consonance principle or with similar rules, but may have such different temporal distributions that it could be difficult to combine them in a single musical figure.
For example, a cell made up solely of long notes can hardly be considered compatible with a second cell built exclusively with short notes, although perhaps they have exactly the same melodic contour and belong to the same scale. In cases like this it is therefore necessary to calculate a second fitness function, parallel to the first.
A possible approach, applicable for systems in which a precise metric is present, is to calculate the duration of the cells and verify if, by putting them together, it is possible to obtain a multiple value of the selected meter. In this way, even in the presence of notes with different durations, it is possible to verify the presence of a general order for the piece. The extent of the deviation from the metric can therefore be used as a fitness value, which will weigh that obtained with the evaluation of the pitch.

3.4.2 Cell Fusion

Once the two cells have calculated their mutual compatibility, the fitness value obtained is evaluated. If it does not exceed a certain threshold, which can be defined by the composer as well as by the ecosystem itself, the cells will reject each one other, moving away from each other and continuing their individual life cycle.

If, on the other hand, the fitness value is higher than the predetermined threshold, the cells will undergo the process of cell fusion, in which they will combine together to form a "melody" made up of the genetic material of the two individuals.

This process, exactly with mitosis, can occur in several ways.

The best acoustic performance of the fusion, intended as the best way in which such occurrence can be perceived by a listener, is undoubtedly obtained through the method of concatenation, in which the two cells form a melody, arranging one after the other. In this way the result will be the most recognizable to hearing, since two cells that could previously be heard at different times and in potentially random order, will now always play consecutively and their evolution will be joined, as if they were a single cell. However, this method may not be satisfactory in the case of contexts in which a certain importance is given to the constructive aspect of the melody, since the simple juxtaposition of two potentially different cells, although still compatible in terms of fitness, will hardly produce a melody consistent with the rules set out in section 2.3.

A second method, which considerably improves the chances of obtaining a coherent melody, is obtained by applying the *Ausfaltung* rule, or Unfolding, explained in section 2.3.2. Specifically, it is possible to achieve the fusion by interspersing notes belonging to one cell or the other while maintaining the general order in which the notes occur in the cells, but not the relative positions between them. In this way it is possible to obtain a melody composed of the recognizable alternation of the material of the two cells, and yet these notes can be ordered, with a certain degree of freedom, to obtain an overall melody that is consistent with the rules of tonal architecture.
Figure 3.8 shows an example of unfolding taken from musical literature, in particular from G. Gershwin's Rhapsody in Blue, in which it is possible to observe how the left hand creates two distinct melodies, which nevertheless appear as a single succession of note.

Figure 3.8: Extract from G. Gershwin's Rhapsody in Blue, Piano score.

A third alternative is that of recombination, in which both cells are broken down into their individual notes, which are then mixed with each other and recombined in such a way as to form a sensible melody. This last possibility, compared to the other two, does not allow easy hearing recognition of the new melody as a product of the fusion, guaranteeing only a vague identification of the fundamental characteristics, such as tonality, general pitch of the notes, tempos and rhythms of the cell, etc. however, contrary to the other methods, it will ensure a greater probability of obtaining a melody consistent with the established constructive principles.

Clearly the choice of the method also depends a lot on the stylistic context of the piece, since certain constraints can be more or less stringent and consequently it is not certain, for example, that the best approach for a tonal musical piece is valid in the same way for an atonal one.

Figure 3.9 shows some examples of fusion of two cells with the three methods described above. It can be observed the immediacy of the concatenation method, whose two bars are simply appended, the greater articulation of the unfolding method, where the notes of the two cells are alternated, preserving the general order but not the relative one, and lastly the method of recombination, which provides a less recognizable but potentially better result from a constructive point of view.

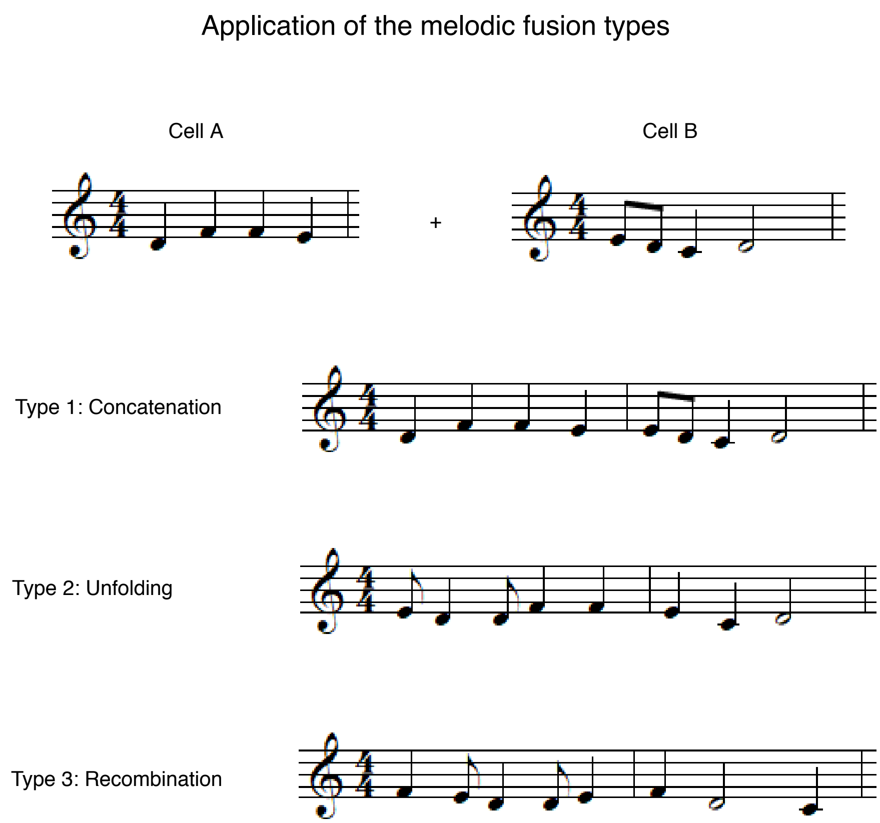

Figure 3.9: Example of possible fusion between two cell using the three proposed methods.

Chapter 4

Melodic Synthesis

In the previous chapter, the forms and methods in which the principles of reciprocal evaluation and mitosis can be applied were discussed. Although in less restrictive areas the rules may be wider and less stringent, this is not the case for the strictly tonal musical context. In this case, in fact, it is not sufficient to carry out an evaluation of consonance between two cells, to verify that they are actually able, by joining together, to create a well built melody. Likewise, the types of cell fusion described need particular sets of rules that define how the various notes can be linked together in sequence. Two melodic cells, therefore, when they meet in the acoustic plane, must necessarily verify that they are able, by merging, to create a valid melody according to the theoretical rules of tonal music, and ensure that the quality of the melody produced can identify their degree of reciprocal fitness.

4.1 The problem of melody building

Combining musical notes in sequence in order to obtain a constructively coherent melody which is valid from the point of view of the rules of tonality, is a problem that although trivial at first glance, is in fact complicated.

Generally, the act of creating a melody is, for a human composer, a natural process as writing a text: the musician usually starts on one end and adds notes until its conclusion. The automation of this process, may be carried out with different methods such as the adaptation to musical tasks of Markov chains [13], random processes in which a relationship is established between, for example, the insertion of a new note and the characteristics of the immediately preceding one. In this way, and further extending the concept, it is possible to create sequences of notes that are not random, but that include some of the fundamental rules of melodic construction, for example the need not to have dissonant intervals.

However, just being able to keep track of the previous note alone isn't enough to compose a sensible melody. Some constructive rules, such as the prohibition of consecutive insertion of leaps of a certain size in the same direction, can be implemented through processes with memory [34], but even in this case, the rules often prove to be insufficient.

As the length and complexity of the melody grows, in fact, it is necessary to introduce more articulated structures for automatic melody composition.

4.1.1 The harmonic problem

The simple juxtaposition of notes in sequence and the rules derived from this practice are not sufficient to give the resulting melody a sufficiently valid constructive aspect to be considered belonging to the tonal musical tradition. In fact, harmony plays an essential role in classical theory and therefore it cannot be neglected during the construction phase.

It is known from music theory that different combinations of harmonic chords can be associated with each sequence of notes. As previously explained in section 2.2.1, each degree of a diatonic scale can be part of three different triads belonging to the harmonic dominion of this system. Assuming therefore that we are harmonizing a particular melody, while neglecting more sophisticated elements such as various modulations, each single note can belong to as many as three different chords, identifying three different harmonic functions. However, according to classical theory, it is possible to restrict this possibility to a lesser number of chords, identified by belonging to the most important degrees of the diatonic system, namely the tonic, the subdominant, the dominant and the submediant, which represent the harmonic regions closest to the tonic in the aforementioned chart of the regions by Schönberg.

This possibility of variation is what allows the arrangement of a melody in different ways and with different properties, and it is also what makes the harmonic analysis process of a piece often complicated. Furthermore, it should be considered that not all the notes of a melody necessarily identify or belong to a chord, since many notes can be elaborations of underlying structures, as discussed in Section 2.2.2.

In the process of automating the creation of a tonal melody, therefore, it is essential to take into account one of the possible compatible harmonies. As already described in Section 3.2.4, it is possible to calculate the best harmony through the table of regions, according to which the harmonic progressions are more musically fluent when carried out between adjacent regions.

In this way it would be natural to think of being able to calculate the reciprocal fitness function of two cells by verifying the possibility of joining the respective notes and thus obtaining the best possible theoretical harmony, but in reality this procedure suffers from a serious defect that makes it inefficient. The combination of continuous unisons or repeated jumps between two notes, in fact, would generate a sequence of sounds to which it is possible to associate a harmony of repeated chords and therefore with a very high fitness value, but the produced sound result would not constitute a satisfactory melody.

This problem could be solved by imposing the constraint that consecutive unisons or octaves are not considered to belong to the same chord, but this circumstance would end up making the evaluation fall into the aforementioned case of the need for a long-term memory, potentially implying the need to keep track of the successive chords from the very first note of the melody.

Given the extent of the problem, it was therefore decided to look for alternative theories, which would allow all the rules of tonality to be applied in a non-linear way, overcoming the problems imposed by such an approach.

4.2 Schenkerian Synthesis

These difficulties can be overcome thanks to the use of theories and assumptions formulated in the Schenkerian analysis.
In classical theory, as well as in the vast majority of musical theories derived from it, each musical element can be considered as a sequence of objects of a varied nature, denoting an inseparable dependence on the necessarily linear aspect of time. A rhythm is therefore a sequence of durations, a melody is a sequence of notes, a harmony a sequence of chords and so on.

On the contrary, the Schenkerian analysis, as already seen in Chapter 2, has the peculiarity of treating each tonal piece of music not so much in a linear form, but rather as the superimposition of different levels, each one obtainable through the process of reduction from the one immediately above.

It follows that it must necessarily be possible to practice the reverse operation, that is a sort of "musical synthesis", which, starting from the definition of the *Ursatz*, allows the construction of a complete piece of music in an analytical way.

For the purposes of this thesis, the formulation of a reduced version of this process will be considered, which is able to be limited to the simple production of melodic lines for the purposes of the mutual evaluation of two cells and their eventual fusion into a single constructively-coherent melody. Given the layered nature of the analytic aspect of Schenker's theories, it is natural to assume that the exact same layered structure can be applied to the synthesis of melodies. Taken from the analysis, there will therefore be three different layers: the *Hintergrund*, the *Mittelgrund* and the *Vordergrund*, each with the specific purpose of grouping all those notes that perform a common function.

- The Hintergrund will contain those notes that, in the melody, make up the constituent elements of the *Urlinie*,i.e. the "melodic voice" of the *Ursatz*.

- The Mittelgrund must contain all those notes that identify the chords of the hypothetical harmony connected to the melody and therefore will be subjected to all the rules of the classical theory of harmony. For simplicity, the adopted harmonic theory will be considered strictly, but with the possibility of a subsequent extension to more complicated and broad theories. As already stated, the search for the notes that make up harmony is an absolutely non-trivial process that can have multiple possible solutions.

- Finally, the Vordergrund will contain all those notes that do not constitute an essential element of the harmonic structure of the piece, which therefore will appear as elaborations or embellishments of the same.

4.2.1 Preliminary operations

Before being able to devote ourselves to the actual construction of a melody it is of primary importance to verify that the material present actually allows one to be created. The essential conditions defined in Chapter 2.2 must therefore be verified.

First of all it is necessary to check the presence of a sufficient number of notes suitable for the generation of the *Urlinie*, which must necessarily be the base on which to build the melody. In the case of fusion between two cells with the qualities defined in Chapter 3, this condition is generally satisfied, however a clarification on the duration of these notes is necessary since, if they were too short, they could not play the role of supporting notes, to which chords can be assigned. Notes that are too short, in fact, are generally elaborations of other ones to which more relevant harmonic functions are assigned.

Once the presence of valid material has been confirmed , we need to make sure to be able to use such material completely, without violating the fundamental laws of good melody building. For example, notes cannot be present that identify, compared to others, intervals greater than a tenth, due to the constraint on the vocal texture, or that are arranged more than an octave away from any other possible note of the melody, to avoid unmanageable outliers. For the rules of strict tonality, moreover, notes that do not belong to the selected scale, in the specific key used, are not accepted.

Failure to satisfy one these conditions results in a total impossibility of creating a melody using the two cells considered, therefore reciprocal fitness will be extremely low and they will reject each other.

4.2.2 *Hintergrund* Rules

The fundamental element of the background layer is the *Urlinie* which, in Schenkerian theory, is present, in its natural form or in one of its possible elaborations, at the basis of every tonal musical piece. For the principle of transference of the *Ursatz*, such fundamental structure has to be present also in a melodic fragment, for it to be considered a complete melody, which is the examined case. It follows that, once the general key of the piece has been established, the melody to be constructed must necessarily be subject to the constraint of containing the notes of the Urlinie, or variants belonging to the chords identified by combining it with the Bassbrechung.

The final note of the melody, therefore, which constitutes the most important of the constraints established by the *Urlinie* must necessarily be a tonic, while inside it, the melody must contain, in any position, a note belonging to the dominant chord, so that, net of subsequent elaborations, a perfect cadence is identified. Similarly, the melody must have, in one of the initial positions, a second note belonging to the tonic chord, thus extending the general cadence to an imperfect cadence. In this case, the mediant degree would be the optimal condition.

As already anticipated in Section 2.3.2 on the elaborations of the *Ursatz*, the initial note may not be exactly the Kopftone of the Urlinie due to the presence of an anacrusis, consisting of one or more notes arranged before the real beginning of the melody . These notes do not form part of the supporting structure of the melody and belong to the harmonic function of the first note, therefore they must be treated in the Vordergrund level.

Although in the subsequent developments of the Schenkerian theories the prominence of the descending Urlinie has been confirmed, for the purposes of this thesis and for a better adaptation to the micromelodic context, the ascending versions and the respective elaborations are also taken into consideration, giving however a greater importance to the first. This can be achieved by assigning a greater fitness value if this case occurs, without however excluding a positive value also for various elaborations and for the ascending case.

4.2.3 *Mittelgrund* Rules

Once the possibility of forming a valid *Urlinie* has been confirmed, the process enters the central phase, that is the *Mittelgrund* synthesis, in which it is assessed the possibility of inserting all those notes which, arranged within the fundamental structure, identify the best harmony that can hypothetically be assigned to the melody. Implementing a unique algorithmic procedure for the *Mittelgrund*, however, is not as simple as for the other cases, due to the absence of a single reference model or of a single solution to the problem.

The first operation that must be carried out is the definition of the melodic contour, by identifying the climax of the melody's outline, usually consisting of the highest note (zenith) or the lowest note (nadir) that can be inserted into it.

Due to the nature of the notes that can be part of the *Mittelgrund*, all notes that do not have a long enough duration to be able to play a relevant role in the construction of harmony must be discarded from this phase. This rule, generally valid, is however subject to some exceptional cases: in fact, if the grouping of notes of short duration, as long as they together constitute a multiple of the beat of the piece, allows to obtain a figure able to uniquely identify a harmonic function, the most important of these notes can be considered part of the Mittelgrund. However, this principle, derived from the third kind of contrapuntal rules, must be considered very carefully and requires careful planning, since it would risk upsetting the balance of the melody, and is therefore neglected in the implementation of melodic synthesis suggested here.

Once the set of notes that can make up the hypotetical harmony has been established, this is achieved by making attempts in search of the best solution, in the same way as the usual harmonic analysis procedure.

The positioning of the hypothetical chords must also be subject to some rules:

- where possible, consecutive unisons are to be avoided, since such repetition can be considered an elaboration without a change of chord and in this case it would fall within the synthesis of the Vordergrund;

- if unisons are not avoidable, they must identify different chords. Similarly, consecutive notes belonging to the same chord must be left to the synthesis of the next layer or, if this is not possible, they must necessarily be indicated as belonging to different chords. This rule can be extended to a larger number of chords in sequence;

- the combination of notes must be adjusted according to the proximity of the hypothetical chords, following the chart of the regions. In this way it is possible to obtain a better harmony and consequently a more linear melody;

- the alternation of only two different chords more than twice. Although this it is not a strict rule, it would be better to follow it, to avoid excessive monotony;

- it is good practice to avoid augmented intervals, a rule taken from those of tonal melody building but accentuated by the difficulty of juxtaposing chords in this way.

4.2.4 *Vordergrund* Rules

Once the *Mittelgrund* procedure is over, the final phase of melodic synthesis is reached. On this layer will be inserted all the notes that are too short to be part of the previous levels or that have been sent forward because their function has already been established.

Notes belonging to this second category, must be treated first, in order not to lose the consistency established in the planning phase of the hypothetical harmony.

The rules applied in the Vordergrund are exactly those already introduced in Section 2.3.1 on musical modeling, applied according to the elaborations of the Schenkerian analysis described in the subsequent section.

However, it is necessary to formulate a scale of precedence for these rules.

1. Passing notes take precedence over any other elaboration, since they make the melody more fluid. If a note can be inserted into an interval of third, this takes precedence over every other case. Moreover, if the inserted note shows a strong resolving tendency towards the second note of the interval, it has to be given precedence. This is the case, for example, of leading tones, supertonics or subdominants.

2. Notes that can fill wide intervals or that identify triads or open chords have to come second. It is always better to loosen wide intervals, and the absolute best way is to insert a note such that a triad can be obtained. Even in this case, the presence of resolving notes has to be treated with the proper priority.

3. *Nebennoten* and unison repetitions may be important, but have to be treated after the previous ones, to avoid the eventuality that a better use of a note has to be put aside in favour of a repetition of lesser melodic impact.

There is another case that falls within the synthesis of Vordegrund, which would be the insertion of an anacrusis. However, this must be carried out exclusively following a rhythmic analysis of the melody. In fact, supposing that we are in a metric musical field, which is however not obvious and not necessarily integrated into the concept of strict tonality, it is first necessary to verify the possibility of inserting such an elaboration of the kopftone, calculating the duration of the notes of both cells that must be fused and verifying that

this value is a multiple of the particular meter adopted.
If this is the case, the anacrusis cannot be inserted into the melody, as this would lead to a general misalignment of the rhythm. On the contrary, if there is excess material, it can be used in this way, provided that the notes that will constitute the anacrusis belong to the tonic chord with which the melody must begin, due to the constraints of the *Urlinie*, or are passing notes that satisfy all the constraints on the intervals described above.

4.2.5 Adaptation of the reciprocal fitness value

Having discussed the method in which two cells merge to create a melody, it is necessary to define how this synthesis process can also be applied to the calculation of their mutual fitness.

In fact, it has been established that it is not enough, in the case of strictly tonal music, to evaluate a simple relationship between the notes of the two cells, but it is also necessary to confirm the possibility of the two cells to form a melody by uniting.

This evaluation can be carried out by assigning particular values to the different stages of the melodic synthesis process, based on their relevance and on the order in which they are addressed. Since the synthesis procedure is not necessarily unique, due to the several ways in which two cells can merge and the multiple solutions to the creation of the *Mittelgrund*, it is necessary a calculation of the fitness function that can take into account the priorities already listed in the previous section, in order to establish the best result and therefore the degree of mutual adaptation of the two cells. This can be achieved with an incremental calculation of the fitness value in the various synthesis levels, with more significant increases in the lower layers and more minute ones as we proceed with the elaborations.

As already seen, the satisfaction of the preliminary conditions is strongly discriminating, since it involves the total inability of the cells to fuse.

If such conditions are met, the nature of the fundamental structure built greatly influences the fitness value. It will in fact be maximum in the case of an *Urlinie* perfectly consistent with the principles of Schenkerian Analysis, therefore having the $\hat{3}$-$\hat{2}$-$\hat{1}$ form. If these notes are not specifically present, it is possible to replace them with other notes belonging to the same functional chord, applying gradually decreasing fitness values where the notes take on more ambiguous harmonic roles. This is the case, for example, of the dominant which,

although technically belonging also to the tonic chord, its fundamental role in the fifth degree chord makes it more inclined to this harmonic function and therefore would involve a lower fitness value associated with the *Urlinie*.
Given the indispensability of the fundamental structure, the fitness values assigned to it must be significant, although the precise quantity depends on how much you want to follow the rigor of the theory in the applied context, and is therefore left to the composer's discretion.

For what concerns the *Mittelgrund*, fitness values can be associated with every possible type of juxtaposition of different chords. As already mentioned, one of the best principles for organizing a succession of chords is through the distance from the previous one - and from the next one - in the table of regions. This very distance value can be used to increase the suitability, making sure that the closer a chord is to its previous one and to its next, the higher the fitness will be. Alternative rules can be added, as for example a reduction in the fitness value if the repeated succession of only two chords occurs, but even in these cases the extent is left to the discretion of the composer.

Finally, with the *Vordergrund* rules, the increase in the fitness value is very small, but still depends on the priority in which they are used.

Chapter 5

Implementation

The principles of cellular music presented in this thesis have been implemented in an interactive application for the generation of simple musical pieces that adopt the described compositional paradigm. This chapter will therefore deal with an implementation of these principles in the specific case of use.

5.1 Tools

5.1.1 Processing

Processing [26] is an open-source graphical library and integrated development environment (IDE) built for the electronic arts, new media art, and visual design communities. It uses the Java language, with improvements such as additional classes and aliased mathematical functions and operations to simplify the programming of the graphical aspects of interactive applications. It also provides a graphical user interface for simplifying the compilation and execution stage.

The program was chosen for the implementation of (A)Live for the convenience with which it integrates the OSC communication protocol, implemented through the oscP5 and netP5 libraries, through which to exchange messages with Python and Supercollider scripts, running in parallel, as well as for the way it facilitates in the creation of highly versatile interactive graphic interfaces.

5.1.2 Supercollider

Supercollider [31] is an environment and programming language originally released in 1996 for real-time audio synthesis and algorithmic composition [20] and then released as a free software under the GNU General Public License.

Since then it has been evolving into a system used and further developed by both scientists and artists working with sound. It is an efficient and expressive dynamic programming language providing a framework for acoustic research, algorithmic music, interactive programming and live coding. SuperCollider is constituted by three major components:

1. **scsynth**, a real-time audio server, that features more than 400 unit generators for analysis, synthesis, and processing, allowing the fluid combination of many known and unknown audio techniques, and the possibility of writing new Ugens in C++, with a repository for users to share them.

2. **sclang**, an interpreted programming language focused on sound, but not limited to any specific domain. sclang controls scsynth via the OSC protocol, and can be used for algorithmic composition and sequencing, finding new sound synthesis methods, connecting external applications or, writing GUIs and visual displays etc.

3. **scide** is an editor for sclang with an integrated help system.

5.1.3 The communication protocol (OSC)

Open Sound Control (OSC) is a protocol for communication among different devices as computers, sound synthesizers, and other multimedia devices that is optimized for modern networking technology and is often use as an alternative to the MIDI standard, as it allows higher resolution and richer parameters. Its advantages include interoperability, accuracy, flexibility, and enhanced organization and documentation, providing everything needed for real-time control of sound and other media processing while remaining flexible and easy to implement.

Among its main features derived from modern networking protocols there is an URL-style symbolic naming scheme, a symbolic and high-resolution numeric argument data, a pattern matching language to specify multiple recipients of a single message, high resolution time tags and "Bundles" of messages whose effects must occur simultaneously.

In the context of this implementation, the OSC protocol has been used for an efficient communication between Processing, Supercollider, and Python, in an unidirectional way between the first two, with Processing as the sole sender and Supercollider as the sole receiver, and in a bidirectional way between Processing and Python.

5.2 (A)Live

(A)Live is an interactive application for the composition and live performance of music produced with the principles of cellular music set out in this thesis. It is built in three different development environments running concurrently: Processing, Supercollider and Python.

All the functions that describe the behavior of cells and habitats are implemented in processing, making use of the Java language, the functions for the automatic and semi-automatic creation of cells are made in Python, while the sound aspect of the application is entirely written in Supercollider.

Communication between the three platforms is achieved by sending custom OSC messages, which are dispatched every operating cycle, that is a discrete time interval, set at two seconds, which marks the most important calculations that are carried out by the system, such as the activation of the evolutionary algorithm, the fusion of two or the calculation of the fitness functions.

A scheme of the architecture is shown in figure 5.1, while the UI of (A)Live as of version 0.3-alpha is shown in figure 5.2.

5.2.1 Implementation of the habitats

The ecosystem is divided into four identical rectangular regions, which are assigned the four identifying pitches of the bass notes and a status variable. Upon insertion of the first cell within the ecosystem, an OSC message containing the value of the pitch and the assignment to the respective habitat is sent from processing to supercollider, where the related Synths are updated. At each control instant, the message sent to supercollider contains the status of each of the four habitats, which will be positive if they contain at least one cell, and negative otherwise. In this way, only the pads of the regions that are activated by the presence of a cell will be played, while the inactive ones will be ignored. To change the activation state, a function to check the presence of cells within the spatial limits of the areas of the four habitats is implemented. For the rest, they play a fundamentally passive role, since in this particular version of the program the values they identify cannot be changed once the execution of the program has been started.

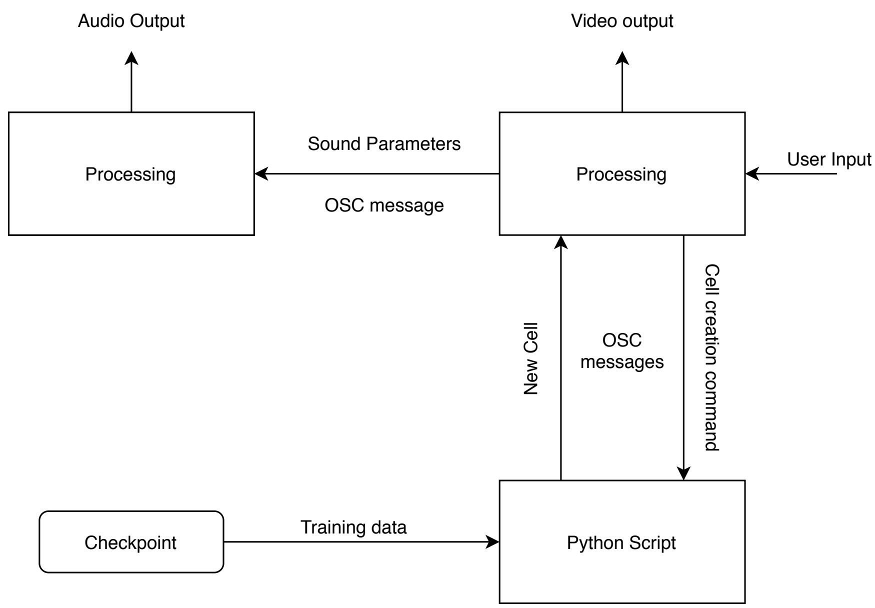

Figure 5.1: The architecture scheme of (A)live, version 0.3-alpha.

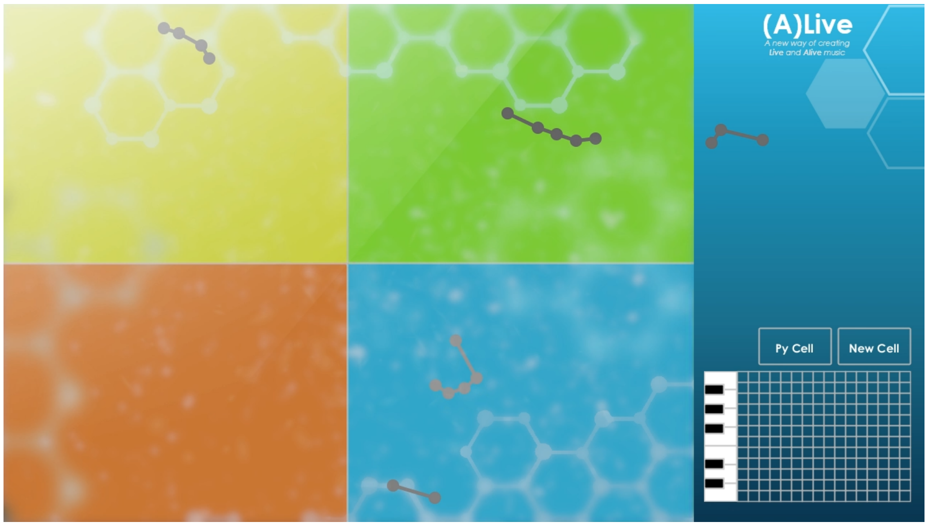

Figure 5.2: User Interface of (A)Live, version 0.3-alpha

5.2.2 Implementation of the musical cells

Melodic cells are represented by objects composed of the following characteristics:

- An identification value;
- A list of pitches;
- A list of durations;
- A list of amplitudes;
- The duration of the life cycle;
- The fitness value related to the respective habitat;
- A PVector that identifies the position, speed and acceleration in the ecosystem;
- A Boolean flag that indicates whether the object is a cell or a melody.

The identification value is necessary for the recognition of the sequence of notes when it is sent to Supercollider via an OSC message, followed by the values of the respective notes.

The life cycle, which is initialized with a predetermined value, decreases at each operating cycle by an amount inversely proportional to the cell's fitness value, multiplied by a decay ratio, also predetermined, which serves to regulate the speed of the process. This value is reset if the cell merges with another one or splits.

The fitness value is initially initialized to -1 when the cell is outside the ecosystem, that is, when it has been composed but not yet activated. Once the cell in question is dragged into a region, this value is updated at each operating cycle according to the respective fitness calculation.

The definition of cell also includes a flag that indicates its nature as a melodic cell or as a melody, respectively, the latter being an extension of the former. The difference between the two is that they can interact exclusively between elements of the same type, but are subject to the same behaviors and the same forms of cellular interaction.

Graphical Representation

The three fundamental dimensions of the nature of each note of the cell, namely pitch, duration and amplitude, are ordered in lists and can therefore change size in the case of growth. To give the system a graphical representation from which the nature of the cells could be guessed by eye, the following approach has been adopted. The melodic cells are represented as sequences of small circles of varying radius and segments of different lengths. Each circle represents a note, and its radius the amplitude of the same, while the length of the immediately following segment represents the duration of the note. The pitch ratios between the different notes are represented, when the cells are not yet arranged within the ecosystem, by the inclination of the segments, so that the outline of the melody is evident, and the average pitch of the notes is represented by the shade of gray with which they are coloured, darker in the case of low notes and lighter otherwise.

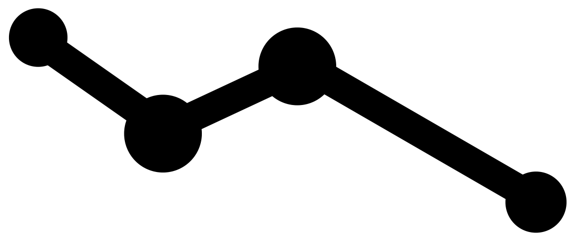

Figure 5.3: Representation of a melodic cell

Movement

The movement of the cells is given by an element of the PVector class, which represents a three-dimensional Euclidean vector, where the three dimensions are identified by the position of the cell - specifically the position of its first note -, its speed and its acceleration.

The position of the cell, in Cartesian coordinates, is sent to the supercollider via an osc message, where it is converted into the correct synth mix based on proximity to the extremes of the ecosystem.

The fitness value, calculated at each instant, affects the speed and acceleration of the cell which increases its own velocity in the case of low fitness and decelerates in the case of high fitness, while the motion in space is equipped with a random component to simulate the small variations of movement of a microorganism in culture medium.

The chaotic motion of the cells is implemented through the application of the steering force formulas [27]

$$desiredVelocity = normalize(position - target) * maxSpeed \tag{5.1}$$

$$steeringForce = desiredVelocity - currentVelocity \tag{5.2}$$

considering in each instant a random position near the cell as the target.

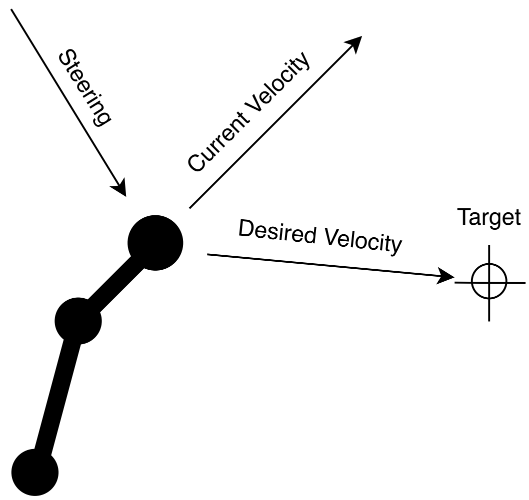

Figure 5.4: Representation of the implemented steering mechanic

These formulas are graphically applied to the first circle of the cell, while the subsequent ones follow it, keeping the distances between them according to their durations, but not their respective inclinations, transforming into a sort of wormlet that gives the idea of a microorganism with of its own life.

At any time, the cells can be dragged by the user, using the cursor, to any other point within the ecosystem, and this action is immediately followed by an update of the data and by sending them to the supercollider in order to update the sound of the habitat and the timbre of the cell.

5.2.3 Birth of a cell

The birth of a new cell may be obtained in different ways: By direct composition, by automatic composition via MusicVAE, by semi-automatic composition through Deep Interactive Composition and by mitosis. This last case is the only one in which the user has no active involvement.

By direct composition

Direct composition is implemented through the use of a composition matrix, which minimizes the function of a piano roll. The rows represent the different possible pitches within an octave, while the columns represent discrete time intervals, i.e. the tatum of the piece, which can be set as a configuration value.

The cells are therefore composed by selecting the desired pitch at the desired time, while the amplitude of the sound is directly proportional to the duration of the mouse click on the desired note. Since the system does not currently provide for the insertion of pauses inside the cells, the empty boxes following a selected box represent the duration of this note.[1]

Through the matrix diagram it is possible to obtain an immediate display of the cell shape, since the length and inclination of the segments can be directly obtained from the calculation of the positions and distances of the selected cells.

Once created, the cell is initialized and inserted into the space dedicated to inactive cells, ready to be introduced into the ecosystem.

By automatic generation with musicVae

MusicVae, as well as Deep Interactive Evolution, is implemented via a python script that runs in parallel with processing and supercollider. When the automatic creation button is pressed, a notification message is sent to the script, in which the magenta configuration files and the trained models are imported.

In particular, it is made use of the pre-trained model for the generation of a two-bar melody, which makes use of a specially downloaded checkpoint file from the Magenta site [21].

The script then proceeds with the creation of a melodic cell, which is checked to verify the satisfaction of the conditions established by the user, namely the minimum and maximum length. A limit is also imposed on the pitch range so that there are no notes below or above certain thresholds. If one of these conditions is not met, the cell is discarded and the script produces a new one, otherwise it is sent as an OSC message back to Processing, which inserts the data into a new object, ready to be introduced into the ecosystem.

Note that, by default, musicVae uses the MIDI system to encode frequencies into notes enumerated from 0 to 128, following the formula:

$$MidiValue = 12 * \log_2(FrequencyValue/440Hz) + 69 \tag{5.3}$$

In this way it is possible to treat the scales in a linear way, without the

[1] The compositional approach chosen does not include the insertion of pauses within the created cells. This choice was made in accordance with the nature of the melodies produced by musicVae and, by extension, by Deep Interactive Evolution, whose melodic cells produced have the same structure.

complications imposed by the use of the lorarithmic scale of frequencies in Hertz. This approach, however, is strongly limiting because it requires the use of the twelve-tone (chromatic) scale system, therefore with the octaves divided into 12 semitones, as well as limiting the frequencies associated with them to those determined by equal temperament.

Consequently, this not only makes it impossible to create microtonal cells using this system, but also raises the need for a systematic conversion of the values obtained, before they are sent to processing, in order to have a versatile application in the type of music produced.

For the conversion is therefore used the inverse of the aforementioned MIDI formula (5.3):

$$FrequencyValue = 2^{(MidiValue-69)/12}(440Hz) \tag{5.4}$$

By Deep Interactive Evolution

Deep Interactive Evolution is implemented, in the Python script, as a following step to the creation of suitable cells, through a slight variant that involves the use of a Variational Autoencoder, in the form of the aforementioned MusicVae, instead of the Generative Adversarial Network described in the definition of the approach [3].

Unlike the autonomous creation of a single cell, in this case a population of ten cells is produced, all created with the same pre-trained checkpoint for two-bar melodies and subject to the same length and range constraints.

The user therefore selects the indices of the preferred cells, which are passed to an evolution function which, by means of them, evolves the vector of latent variables, performing the crossover and applying a mutation, with very low probability.

The process is therefore iterated until a cell appears that the user considers to be the optimal solution, after which it is selected, converted into frequency values with the aforementioned formula and sent to processing through the usual OSC message, to be subsequently used as in the case fully automated composition.

5.2.4 Fitness function

The fitness of each cell with the habitat in which it is located is calculated for each operating cycle and a different approach is used in the general/microtonal case and the strictly tonal one.

Atonal/Microtonal Fitness

In the atonal/microtonal case, the fitness value is obtained by calculating a ratio between the frequency of each note of the cell and the bass frequency of the habitat. This ratio is therefore compared with a table which shows the degree of consonance based on the type of interval it identifies.

In the case of a dodecaphonic system, the ratios and the relative compatibilites are are depicted in table 5.1.

x	**Intervals**	**Frequency Ratio**	**Compatibility**
1	Unison	1.00	1.0
2	Minor Second	1.06	0.0
3	Major Second	1.12	0.0
4	Minor Third	1.19	0.5
5	Major Third	1.26	0.5
6	Perfect Fourth	1.33	1.0
7	Augmented Fourth	1.41	0.0
8	Perfect Fifth	1.50	1.0
9	Minor Sixth	1.59	0.5
10	Major Sixth	1.68	0.5
11	Minor Seventh	1.78	0.0
12	Major Seventh	1.89	0.0
13	Octave	2.00	1.0

Table 5.1: Frequency ratios of intervals and their compatibilites.

In the case of a microtonal system, the situation becomes a little more complicated, first of all due to the lack of a univocal temperament that allows the use of precise values, and secondly to the difficulty of speaking of real and perceptible "consonance". It has been therefore decided to remedy this problem by extending the scheme already used for the twelve-tone context by inserting intermediate values among those adopted in it, in conjunction with the insertion of quarter tones, and by adapting the compatibilities with values in between those of the semitones.

x	**Intervals**	**Frequency Intervals**	**Compatibility**
1	Unison	0.98 - 1.02	1.0
2	Subminor Second	1.02 - 1.05	0.5
3	Minor Second	1.05 - 1.08	0.0
4	Neutral Second	1.08 - 1.11	0.0
5	Major Second	1.11 - 1.14	0.0
6	Subminor Third	1.14 - 1.17	0.25
7	Minor Third	1.17 - 1.20	0.5
8	Neutral Third	1.20 - 1.24	0.5
9	Major Third	1.24 - 1.28	0.5
10	Narrow Fourth	1.28 - 1.32	0.75
11	Perfect Fourth	1.32 - 1.36	1.0
12	Wide Fourth	1.36 - 1.40	0.5
13	Augmented Fourth	1.40 - 1.44	0.0
14	Narrow Fifth	1.44 - 1.48	0.5
15	Perfect Fifth	1.48 - 1.52	1.0
16	Subminor Sixth	1.52 - 1.57	0.75
17	Minor Sixth	1.57 - 1.62	0.5
18	Neutral Sixth	1.62 - 1.67	0.5
19	Major Sixth	1.67 - 1.72	0.5
20	Subminor Seventh	1.72 - 1.77	0.25
21	Minor Seventh	1.77 - 1.83	0.0
22	Neutral Seventh	1.83 - 1.88	0.0
23	Major Seventh	1.88 - 1.93	0.0
24	Supermajor Seventh	1.93 - 1.98	0.5
25	Octave	1.98 - 2.02	1.0

Table 5.2: Frequency ratios of microtonal intervals and their compatibilites.

Once the compatibility values have been assigned to each of the notes of the cell, the average value is calculated to obtain the fitness of the cell in relation to the current habitat. This value is therefore saved within the cell itself and used as a coefficient to regulate acceleration and evolution.

Tonal Fitness

The tonal fitness function is implemented in a similar way, but involves an extra level of calculations. As in the atonal case, each note is compared with that of its own habitat, but in this case the compatibility value does not represent the degree of consonance of the interval, but whether or not it belongs to the scale built on the degree of the general key identified by the bass note of the habitat. For example, if the key of the piece is C major and a cell is in the habitat identified by the note F, each note of the cell will be compared with the F major scale. Every note that belongs to this scale is therefore considered compatible, while every note that does not belong to it is considered incompatible. This comparison is therefore made a second time in relation to the general key of the piece. Each note will therefore have two different fitness values, of which the average will be calculated, and finally the mean value of all the compatibilities of the different notes will constitute the fitness of the cell.

5.2.5 Evolution

Cellular evolution has been implemented through a genetic algorithm, entirely localized in the Processing application, which is activated at each operating cycle on each of the active cells in the ecosystem.

First, a population of ten individuals, or "chromosomes", is created. Each chromosome represents a copy of the cell, in which one of its notes, randomly chosen , is increased or decreased, also in this case randomly, by a certain value. This value is a semitone, in the dodecaphonic atonal case, or a quarter-tone in the microtonal case, while in the tonal context the note is increased according to the scale degrees, therefore by a semitone or a whole tone, according to the context. In this way, the cells are always kept within the predetermined scale, satisfying one of the fundamental conditions of tonal melodies (see chapter 2.3.1).

For each of these chromosomes the fitness value is calculated with the above mentioned methods, after which they are sorted by decreasing fitness. Only the first three chromosomes are then selected and the crossover and mutation functions are applied, thus creating a new generation of individuals.

Each new individual is created by comparing two of the chromosomes selected from the previous generation and each note is randomly chosen between those of the two cells, after which it is subject to a low probability mutation that may increase or decrease its pitch in the same way as how the first generation is initialized.

The process is repeated for a total of ten times, at the end of which the cell with the best fitness value is replaced with the initial one.

To avoid stagnation in local optimals, an elitism function has also been implemented, which consists in copying a number of the best chromosomes of one generation directly into the next, without subjecting them to crossover.

The number of generations, of individuals, of elite chromosomes and the probability of mutation are expressed in freely modifiable configuration variables to be adapted to the user's preferences.

5.2.6 Growth

The cell's ability to grow is verified at each operating cycle. This possibility is determined by a random number multiplied by the fitness value, so that a very high fitness can considerably affect the probability that a cell has to grow, and vice versa.

Growth consists in the insertion, at the head or tail of the cell, of a new note of random value, at a distance shorter than an octave, up or down, with respect to the adjacent note, in order to satisfy the melodic constraint on wide jumps. The random value is mitigated by the fact that growth is arranged immediately before the evolutionary process.

The duration of the added note depends on the current state of the cell in relation to the predetermined metric. In fact, in order to avoid that, during the fusion phase, the recombination of notes causes frequent syncopations[2], it is necessary to ensure that the new cells tend to "round" the rhythm to make it compatible with the metrics of the composition. As a result, the following mechanism has been implemented.
The deviation of the duration of the cell in question from that of the metric is calculated, through a modulus operation. The new note will therefore have a probability of being assigned a duration based on that remainder. If this is zero, the new note can take on any value, to avoid the tedious repetition of notes of the same length.

For example, let us suppose to have selected a metric in quarters, and to have set the tatum, intended as the minimum possible duration of a note, to one sixteenth. If the considered cell has an overall duration multiple of four, the

[2]Syncopation, in music, is the displacement of regular accents associated with given metrical patterns, resulting in a disruption of the listener's expectations and the arousal of a desire for the reestablishment of metric normality.[7]

new note can take on any value.
If the remainder is equal to three, the new note must necessarily be within this duration, and consequently can only last one eighth or one sixteenth, and so on.

This approach, however, causes a distribution problem in the case of the availability of multiple choice of durations, since if these possibilities were uniform, there would be a predominance of the appearance of short notes over long ones. It is therefore necessary to adapt this probability according to table 5.3, calculated based on the weights of the insertion of the various durations in the different cases:

Rest	**Sixteenth Note**	**Octave Note**	**Quarter Note**
0	1/7	2/7	4/7
3	1/4	3/4	
2	1/3	2/3	
1	1		

Table 5.3: Probability weight of note durations in a quarter-based metric

5.2.7 Mitosis

Each cell is subject to a maximum length constraint, understood as the number of notes inside it, set by a configuration value that can be modified by the user.

At each trigger of the growth function, the number of notes present in the cell in question is checked and if the maximum threshold is exceeded with the adding of a new note, the cell will break in two. For simplicity and to obtain a better diversity of the material produced by the process of mitosis, in this application has been implemented the method of halving. The first cell, composed of the notes that were at the head of the parent, replaces it, keeping its identifier but resetting the life timer and updating the fitness value, while the second is added as a new cell and is subject to a force of repulsion that distances her from her sister. From this moment the two cells are and behave as totally distinct entities.

5.2.8 Apoptosis

As already treated before, when a cell is created a timer is set that determines its life. This timer is decreased at each operating cycle, multiplied by the inverse of the fitness value, which consequently will cause the timer to slow down in the event of high compatibility with the habitat, and accelerate otherwise. The timer is only reset in case of mitosis or in case of cell fusion. When the timer runs out, the cell is declared dead, removed from the ecosystem, and the instance destroyed irreversibly. A message is then sent to Supercollider, which eliminates the cell from the play buffer.

5.2.9 The reciprocal atonal fitness function

In each instant, each cell keeps track of its position in the ecosystem through a couple of Cartesian coordinates. When two cells are in proximity to each other, that is when the difference between the distances is less than a certain threshold on the range of action, set through a configuration variable, a mutual fitness calculation is performed.

In the atonal and microtonal case, as regards the compatibility of the pitches, the reciprocal fitness function is similar to that between the cell and its habitat, in the sense that it uses the same parameters, however, it is calculated by first obtaining the fitness between the first cell and each note of the second one, and subsequently calculating the average of these fitness values.

The compatibility of the durations is then checked. Since the application provides for the adaptability of the system to a musical style without metrics, this rhythmic fitness function is implemented by verifying the difference, in milliseconds, between each of the notes of the two cells, according to table 5.4:

Duration difference	Compatibility
0.00 - 0.05	1.00
0.05 - 0.10	0.95
0.10 - 0.15	0.90
0.15 - 0.20	0.85
0.20 - 0.25	0.80
0.25 - 0.30	0.75
0.30 - 0.35	0.70
0.35 - 0.40	0.65
0.40 - 0.45	0.60
0.50 - 0.60	0.50
0.60 - 0.70	0.40
0.70 - 0.80	0.30
0.80 - 0.90	0.20
0.90 - 1.00	0.10
1.00 - +inf	0.00

Table 5.4: Non-metric duration compatibilities

As in the case of pitches, this calculation is first performed between one cell and each note of the second, and then the average of the values obtained is considered the reciprocal rhythmic fitness value.

Once both pitch fitness and duration fitness calculations have been obtained, the average value is computed, which will represent the total compatibility value of the two cells.
If this number exceeds a threshold set as a configuration variable, the two cells merge with the concatenation method, with the reset of the life cycle and a new fitness calculation to initialize their motion.

5.2.10 Tonal fitness implementation and fusion

In the tonal case, things are further complicated, as it is no longer possible to perform a fitness calculation based on a simple comparison.

On the contrary, a series of functions have been implemented that carry out the melodic synthesis of the two cells, verifying the conditions and the subsequent efficiency of the process of building a constructively coherent melody, as described in chapter 4.

The fitness resulting from this calculation will therefore be positive if the material present in the two cells allows the effective synthesis, otherwise it will be negative. If positive, the fitness is subsequently compared with a threshold value, set through a configuration variable, which indicates the minimum degree of "melodic goodness" that the product of the fusion must show in order to be considered valid, currently set at 0.5.

The first step is to convert the frequency values into midi values, according to the formulas already shown in paragraph 5.2.3, in order to simplify the calculations.

The fusion process, implemented in the recombinatory mode, which coincides with the calculation of fitness is therefore divided into four stages, that will be individually analysed.

1. Preliminary Conditions

The two cells are examined to verify the preliminary conditions: First, each note is compared with all the others to verify that there are no two whose distance from it is greater than 12 semitones, that is an octave.
Then, the notes are compared with a reference vector to verify that they all belong to the scale relative to the pre established general key and mode (major or minor) of the piece.

If even just one of these conditions is not verified, the operation is interrupted and the assigned reciprocal fitness will be null.

2. Hintergrund

In the *Hintergrund* phase, a list of potential candidates for the three functions of the *Urlinie* is first created. The candidates are selected from the notes of both cells, they must belong to the tonic and dominant chords of the established key and have a duration greater than or equal to the tatum * the metric value. If this list cannot be created, the process is interrupted and the fitness will be null.

The roles of the *Urlinie* are therefore assigned starting from the last note, which must belong to the tonic chord, followed by a note belonging to the dominant chord and a third one which must again be part of the tonic chord. Since the fifth degree can belong to both the tonic and dominant chords, if assigned to one of the roles, the possibility of completing the next role in the absence of it is verified, otherwise it will be replaced.

Based on the nature of the notes inserted in the *Urlinie*, the fitness function is increased according to table 5.5:

		Grade						
		I	II	III	IV	V	VI	VII
Role	Tonic (Beginning)	0.1		0.167		0.05		
	Dominant (Middle)		0.167			0.1		0.05
	Tonic (Ending)	0.167		0.1		0.05		

Table 5.5: Fitness increase of Urlinie degrees

Once all the three notes that constitute the *Urlinie* have been established, the indices of these are saved in a list, while the chords identified by them, that is Tonic - Dominant - Tonic, are recorded in a second one.

3. Mittelgrund

As in the case of the *Hintergrund*, the *Mittelgrund* begins with the creation of a list of potential candidates, which also in this case must have a duration greater than or equal to the tatum * the metric value.

The problem of inserting notes so that the chords identified by them meet all the necessary constraints is not trivial and therefore requires the use of a backtracking algorithm that allows the algorithm to modify previous entries if the current one cannot be made.

This is achieved through the recursive call of the melodic construction function before finalizing the insertion of a particular note. This function first calculates all the possible chords for the note to be inserted, after which it checks the satisfaction of the conditions in the possible positions in which it can be introduced. These positions are always and only two, one immediately before the second element of the *Urlinie* and one immediately before the end. If neither of the two positions satisfies the constraints, the function returns a negative result to the previous call which, if it has any available, tries to insert the note in another position, and so on.

With each successful insertion, the selected hypothetical chord is recorded in the correct position in the chord list and the reciprocal fitness is increased by a value directly proportional to the proximity of the chord to the immediately preceding one.

4. Vordergrund

The *Vordergrund* level is the last and most straight-forward of the three.

After having collected all the remaining notes, these are scanned to check if it is possible to insert them in the different ways listed in chapter 4.2.4, in the order in which they are reported, increasing the fitness value each time by a decreasing amount as you proceed conditions.

For all the notes that cannot be entered as elaborations of the *Mittelgrund*, the best position is calculated, searching for the one that minimizes the interval they constitute with the previous note and the next one. This type of entry does not involve any increase in the fitness value.

5.2.11 A note sound design

The sound aspect of (A)Live was created with Supercollider, a very versatile tool that allows an agile interaction with Processing. Through it, five different synths have been created, one of which is a discretely articulated synth pad dedicated to the sound of the habitats, and four represent the pure timbres arranged at the four extremes of the ecosystem.

The OSC messages received by Supercollider contain the values and positions of each active cell, which will then be inserted into an audio execution buffer through the use of PBind. Its positional coordinates are used to balance the amplitudes of the four synths in a mix that is assigned to the respective cell, in such a way as to give it a distinctive timbre.

The playing of the notes is sequential but not cyclic, in the sense that sounds of different cells can overlap if a cell begins to play before the end of the previous one, and the order of execution is not necessarily predetermined, but subject to a random variable. All of this was achieved through the use of PSpawner and EventStreamPlayer.

Chapter 6

Evaluation

To verify the validity of the compositional approach presented in this thesis, a survey sample of subjects was selected who, after a presentation of the system, were asked to fill in a questionnaire.

The sample was selected from a heterogeneous group of musicians, with various backgrounds and different skills, yet united by having a recognized educational qualification, in Italy or Switzerland, in the musical field.

Since it was considered premature to perform a direct testing of the (A)Live prototype by users, due to the difficulty in installing and managing the various applications on which it is built, and since such an evaluation method would necessarily have biased the opinion of the interviewees on strictly implementative aspects, it was decided to adopt the following approach.

Each subject was sent a file package as follows:

- A brief description of the compositional paradigm, duly summarized but complete with all the aspects described in this thesis.
- Three demonstration audio files, produced entirely with (A)Live, the computer application that implements the principles of cellular music described in chapter 5. Of these files, two were made with the methods and settings for producing tonal pieces, and they are differentiated from each other for having been created using different tonalities, modes and parameters (different cell lengths, different tatum etc. . .). The third file was created with the microtonal music settings, in order to show the potential of the application in various areas of use.

- A short video file, lasting about a minute and a half, showing the use of (A)Live for music production, in which all the different operations and mechanics implemented have been condensed and highlighted for a better demonstrative clarity.
- An evaluation questionnaire of the presented compositive principles, to be filled in following the reading and acknowledgment of all the aforementioned demos.

In total, 23 survey responses were collected. In the case of open answers of particular relevance, they will be translated from the original Italian and for privacy reasons the author's full name will not be reported but only his initials.

6.1 The Questionnaire

This section contains the full text of the questionnaire submitted to the survey sample. The questionnaire was originally written and answered in Italian, however here will be reported the English translation.

6.1.1 Background Questions

- What music qualification do you have?
  - Music School Diploma (Switzerland)
  - Conservatory Degree (Old System)
  - Pre-Academic Diploma (Pre-College in Switzerland)
  - Bachelor's Degree
  - Master's degree
  - PhD
- Are you a composer? (Yes / No)
- If so, how many years of experience do you have behind you?
  - 5-10
  - 11-15
  - 16-20
  - 21-25

  - 26+

- Do you prefer a particular compositional movement? If so, which one? (Yes / No and eventual answer.)

6.1.2 Contextual Questions

- Have you ever used Computer-Assisted-Composition before? (Yes/ No)
- Did you already know examples of the use of genetic algorithms in the compositional field? If so, which ones? (Yes/No and eventual answer.)
- Do you know other compositional paradigms that make similar use of genetic algorithms and neural networks to define rules for musical composition? If so, which ones? (Yes / No and eventual answer.)

6.1.3 Questions on the Paradigm

- Do you know other musical genres/styles that already make use of cell structures or musical motifs? If so, which ones? (Yes / No and eventual answer.)
- This compositional paradigm provides a series of mechanics by which melodic cells can be organized in a composition. In your opinion, could this paradigm be applied to already existing genres/styles that make use of cells or musical motifs? If so, which ones?(Yes / No and eventual answer.)
- Cells are constantly evolving and moving in the bidimensional space, with the possibility of growing, merging, splitting, dying. How do you evaluate the compositional concept of self-evolving music? (Likert-like scale answer from 0 to 5)
  Please, motivate your answer.
- Some aspects of the musical framework are in the hands of the composer, while others are managed by the machine, after having been set by him/her: how much room for action on the system do you think the composer has, in order to consider a piece produced with it his own composition? (Likert-like scale answer from 0 to 5)
- The rules with which the fitness functions are calculated or with which the cells are created and evolved can be modified at will by the composer. How

do you evaluate the possibilities of the paradigm to be explored and elaborated on from a compositional point of view? (Likert-like scale answer from 0 to 5)

- How interested would you be in using or experimenting on this musical framework for compositional purposes?(Likert-like scale answer from 0 to 5)

6.1.4 Questions on the demos

- Audio and video files demonstrating a possible implementation of the compositional paradigm are attached to this questionnaire. Do you think that the constructive and evolutionary principles (nature of the cells, evolution, fusion, etc.) are sufficiently evident in the audio product? (Likert-like scale answer from 0 to 5)

- In the tonal demos, use is made of a melodic synthesis system based on Schenkerian Analysis. Were you aware of the existence of this theory? (Yes/No)

- If so, do you consider the melodic synthesis method adopted consistent with these principles? (Yes/No)

- Do you know other tools for Computer-Assisted Composition that make practical use of Schenkerian Snalysis? If so, which ones? (Yes / No and eventual answer.)

6.2 Survey answers

6.2.1 Part 1: Background Answers

The first part of the survey consisted of simple general questions to know the background of the respondents and thus be able to perform a better analysis of the results based on the experience and skills of the users.

The survey sample was selected from musicians from both Italy and Switzerland, countries that adopt two different academic systems, in order to optimize the diversity between the musical backgrounds and expertises of the interviewed subjects.

Educational Qualification

The first question was about the respondent's educational qualification. For this survey, only musicians with a recognized qualification in at least one of the two countries where the survey was conducted were selected. The university systems in Italy and Switzerland are slightly different and several reforms have been implemented in recent years, so some qualifications can be considered equivalent to each other, namely the old system of Italian conservatory and the newer pre-academic or pre-college course.

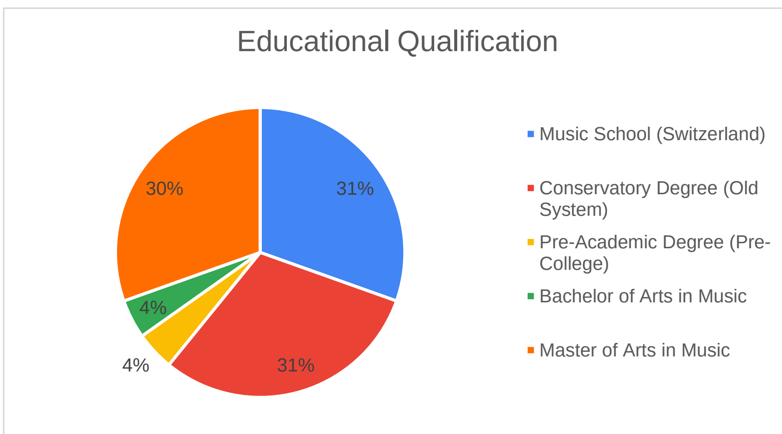

Figure 6.1: Background question n. 1

The answers show an almost uniform distribution of the subjects interviewed on the various definitive musical titles, with the exception of two answers belonging to titles that are of a transitory nature, namely the pre-academic diploma and the bachelor of arts.

Composers and Performers

The second question was aimed at distinguishing between those who practice musical composition as a professional activity and those who do not and are, therefore, musicians dedicated to performance.

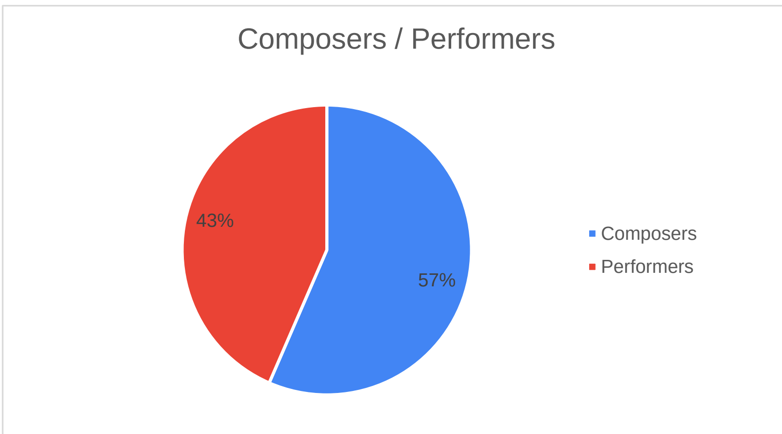

Figure 6.2: Background question n. 2

Of the 23 people who participated in the survey, 13 replied that they are composers, while 10 said they are not.

Composition Expertise

The composers were therefore asked the number of years of experience they have in the field and the possible preference for a particular compositional style they have adopted.

3 of the 13 composers declared that they had an experience of less than 5 years, 4 between 6 and 10, 3 between 11 and 15, 1 between 16 and 20 and finally 2 have over 26 years of experience in the field of music composition.

Only 8 composers expressed a specific style preference, of which half indicated contemporary electronic or electroacoustic music.

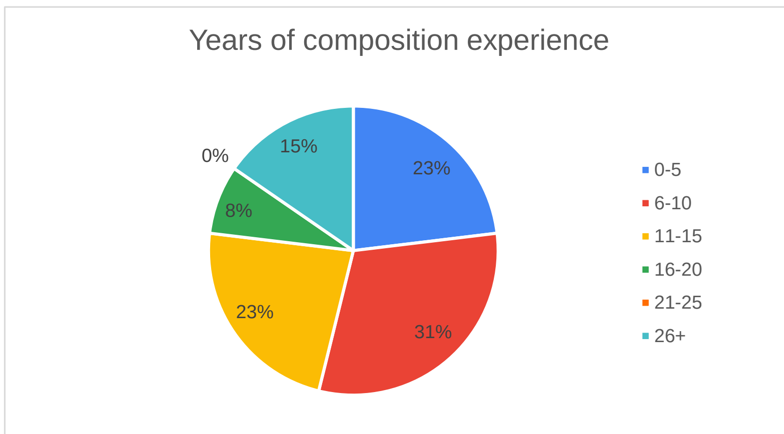

Figure 6.3: Background question n. 3

6.2.2 Part 2: Contextual Answers

This section of questions was intended to test the diffusion, within the musical world to which the potential target of this work belongs, of computer-assisted composition techniques, as well as to verify the actual novelty constituted by the compositional paradigm exposed in this thesis.

Particular emphasis has been placed on tools which, like the one presented here, make active use of genetic algorithms and neural networks for the generation of rules and of compositional principles.

Usage of Computer-Assisted Composition

The first question of this section was aimed at verifying the widespread use of computer-assisted composition techniques among musicians. Since these techniques are not reserved exclusively for composers, but can also be used by performers to develop cadences, solos or improvisation passages, the question was addressed to all participants, with the following results.

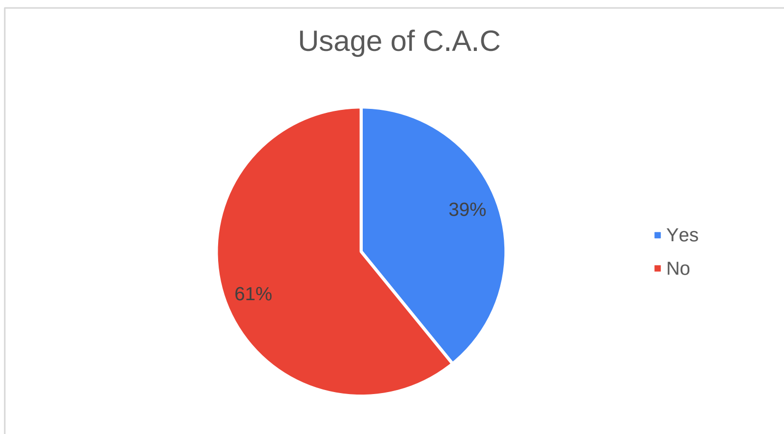

Figure 6.4: Contextual question n. 1

In particular, 8 of the composers declared that they have already made use of C.A.C. techniques, while 5 did not. All the composers who have used it have a conservatory diploma of the old system, a bachelor or master of arts in music, while only 1 performer declared having used these instruments.

Knowledge about Genetic Algorithms for composing music

The second question of the section was aimed at the specific case of Computer-Assisted Composition systems that make use of Genetic Algorithms. This question is completely independent from the previous one as the use of these systems is not conditioned by knowledge of them.

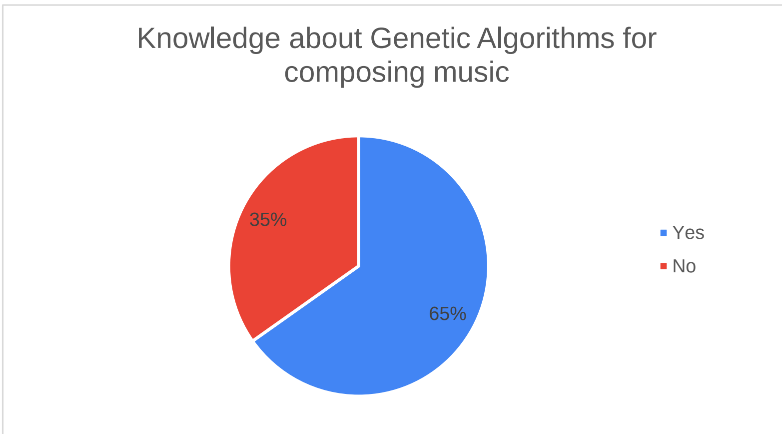

Figure 6.5: Contextual question n. 2

All but two of those who answered affirmatively to the previous question answered in the same way in this question, while only one of those who answered affirmatively to this question answered negatively to the previous one.

If the answer is affirmative, it was subsequently asked to mention some of the systems known to the respondents. Among the replies reported, of particular interest are: Evosynth [12], Hinicinichnia[35], GenOrchestra[8] and various libraries for music processing software.

Similar compositional paradigms

The next question is intended to validate the novelty of the approach presented in this thesis by asking the musicians if they know other compositional paradigms that use genetic algorithms and neural networks in a similar way for the generation of musical rules.

19 musicians replied negatively, confirming in the absolute majority the lack of significant evolutionary technological approaches aimed specifically at the creation of new compositional techniques.

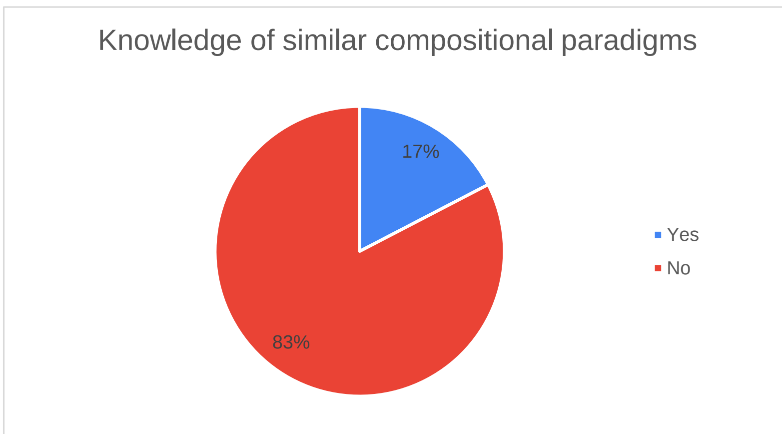

Figure 6.6: Contextual question n. 3

Of the four affirmative answers, for which the motivation was given, two mention instruments that give the composer the possibility of using Neural Networks for compositional purposes, while the other two report interesting musical experiments carried out in the past that draw inspiration from natural phenomena, such for example "Botanical Rhythms"[25].

6.2.3 Part 3: Answers on the Paradigm

This section of questions is aimed at obtaining an evaluative opinion on the compositional principles described in the thesis, their musical and artistic potential and their applicability to the different existing musical contexts that make use of a cellular structure, as well as to the creation of original compositions belonging to a new musical style.

Some of the answers, by the very nature of the covered topics , may be subject to the personal taste of the participants, therefore it was decided to adopt a Likert-like scale, where 0 indicates a totally negative judgement and 5 an extremely positive one. In the case of questions requiring particularly subjective answers, the respondents were subsequently asked for their motivations.

Other musical genres using cells or motifs

The first feature that we wanted to verify through the questions on the paradigm is the effective applicability of the concepts described to various musical genres. In order to do this, it is first necessary to verify the presence of compositional styles or techniques, known by the subjects, which make direct use of musical cells or motifs, as described in section 3.1.2.

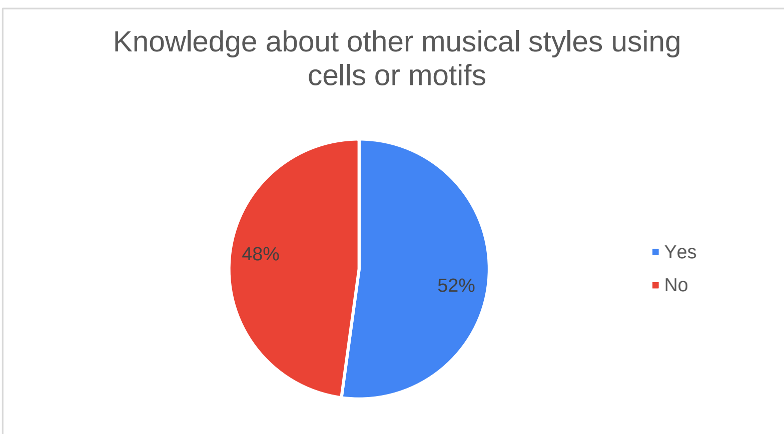

Figure 6.7: Question on the paradigm n. 1

12 responses were affirmative and were accompanied by a specific motivation, by citing one or more genres that satisfy this characteristic. Among these, the most reported are: Instrumental and Electronic Minimalism, Techno Music, Intelligent Dance Music (IDM) and the works of specific composers such as Voisin, Beyls and Xenakis. Some replies pointed out that micromelody thematicism is a very widespread technique also in classical music from the sixteenth century to today.

Applicability to other musical genres

It was therefore asked whether the approach described by the compositional paradigm could be used in order to reproduce, extend or explore already existing musical genres, which may be those mentioned in the answer to the previous question or other genres that could, in the opinion of the respondents, benefit from such an application. The answer in this case was very positive, with 20 affirmative and 3 negative replies.

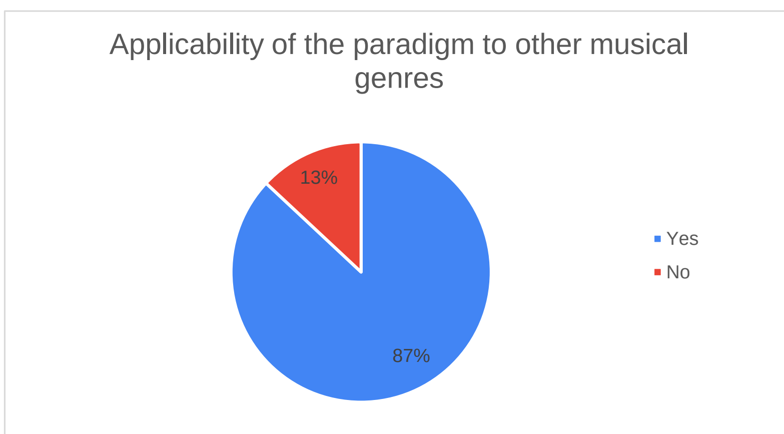

Figure 6.8: Question on the paradigm n. 2

Also in this case it was asked to quote examples of musical genres to which such a paradigm can be applied, receiving a wide range of responses: Ambient music, Drone music, Minimalist Music, Avantgarde Music, Theater Music, Stochastic Music, Techno Music, Classical Contemporary Music, Doom Metal etc...

Here are some of the more extensive answers:

> ”This paradigm could, by appropriately calibrating the correspondences between "habitats", be applied to different compositional genres, even very different from each other. Interesting applications could be found in cultured minimalism, but also to all those genres that exploit archaic frequency organizations, of popular or "ecclesiastical" matrix.” (F.V.)

> ”I am reminded of the "flexible" particle approaches or those linked to linguistics, prosaics and phonotactics to "elasticise" the forms according to various parameters and thus create a multilevel dialectic.” (O.D.)

Personal judgement on the concept

The next question asked to express a general personal judgment on the concept of cellular music as set out in this thesis and as showed in the demonstrative audio played to each of the respondents.
65% of the answers obtained were very positive or extremely positive.
Also in this case, the participants were asked to answer briefly, giving the reasons for their choice.

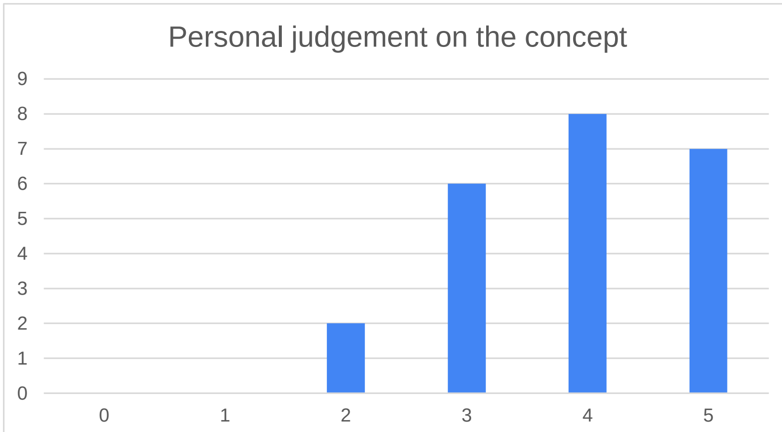

Figure 6.9: Question on the paradigm n. 3

At this point it is interesting to note, in the answers to 2 or 3, the division between the opinion of the composers, according to which the system can be made even more detached from the direct action of the user, and of the performers, who wary of the degree of freedom assigned to the automated aspect.

The answers between 4 and 5 express themselves very favorably on the novelty of the approach, especially for the modeling of natural mechanics, and on the possibilities it opens up to further explore existing genres and to make the algorithmic composition more dynamic. Some of them propose further developments for a greater generalization of the rules, aimed at instrumental composition, and the use of even more in-depth mechanics to expand the amount of emotional information that can be transmitted by a composition that adopts this paradigm.

Freedom of expression

The fourth question was aimed at verifying the degree of freedom granted to the composer. Some of the aspects of the paradigm, in fact, can be established and explored by the user, such as manually composed cells, fitness functions, fusion and mitosis rules etc., while others mechanics are fixed points that are managed independently by the machine.

It is therefore important to establish if a user who uses this compositional technique can consider a piece produced with this approach to be his own composition, or if the extent of the constraints imposed by the system is such as to deny the composer's freedom of expression.

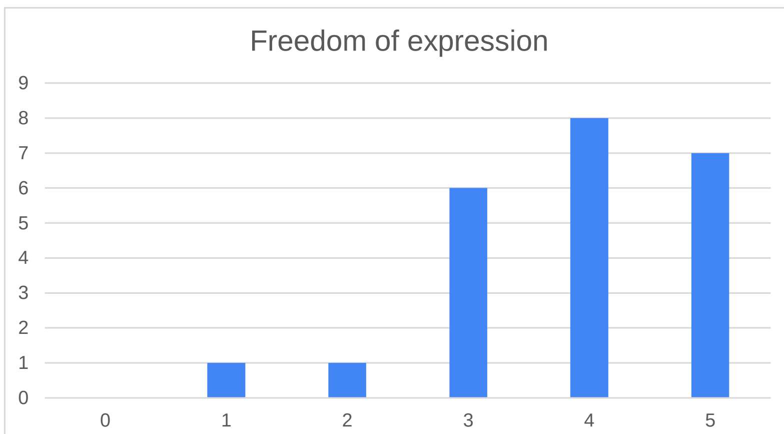

Figure 6.10: Question on the paradigm n. 4

Also in this case 65% of the answers are very or extremely positive, while the others also include those of the respondents who in the previous question had already expressed the desire for greater freedom, in one case, and lesser in the other.

Artistic exploration opportunities

In this question we wanted to verify the potential of the compositional paradigm to allow users a consistent possibility of artistic exploration, through the application of different fitness functions, different rules for the fusion and evolution and different ways of composing the cellular material to be included in the ecosystem. This evaluation is important to demonstrate that this compositional paradigm is endowed with possibilities for future developments and that it grants a composer who uses it a sufficiently wide range of ways in which to express his art.

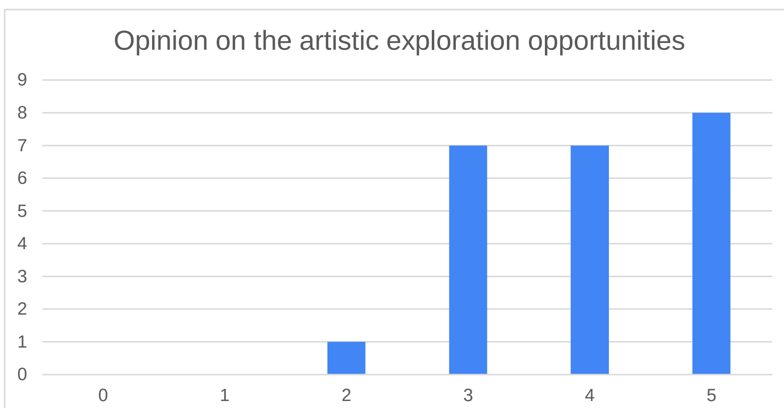

Figure 6.11: Question on the paradigm n. 5

The percentage of very or extremely positive responses once again remained at 65%, with the majority of ratings at 5.

Interest in using the paradigm

The sixth question is aimed at verifying the interest of the respondents to use the compositional paradigm or to experiment on the principles of cellular music.

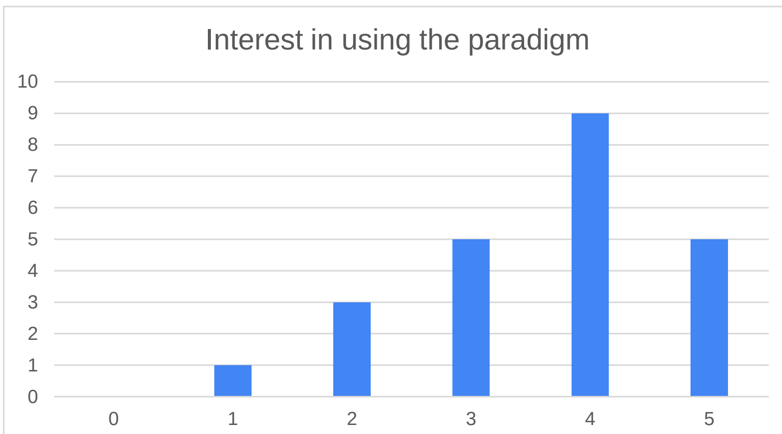

Figure 6.12: Question on the paradigm n. 6

It should be mentioned in this case that the answers of 1 or 2 come from users who have declared that they are not composers and have never made use of Computer-Assisted Composition techniques.

6.2.4 Part 4: Answers on the demos

In this section, the effectiveness of the audio and video demos shown to the participants was examined for better clarity regarding the compositional principles covered in the thesis, as well as their applicability through the (A)Live application, as presented in chapter 5.

In particular, we wanted to validate the choice of using the melodic tonal synthesis approach developed on the principles of Schenkerian Analysis, a powerful musical tool never fully explored in the computer engineering field.

Clarity of the demos

The first question of this section is aimed at verifying the effectiveness of the demo files in showing all the aspects of cellular music trated in this thesis, and at the same time assessing the recognizability of the described compositional principles in an audio product made with them.

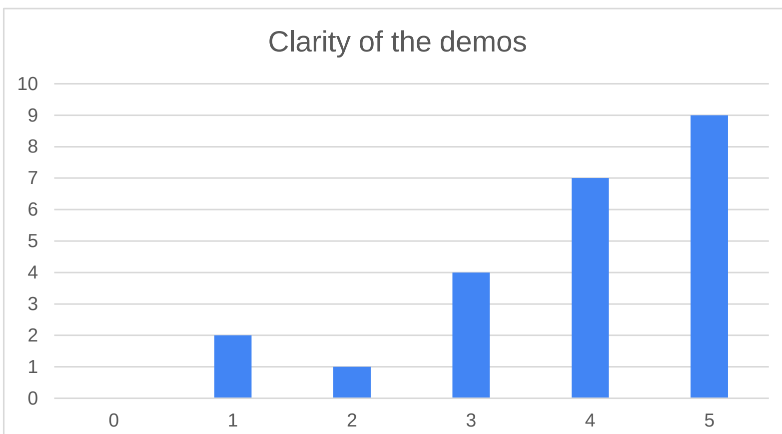

Figure 6.13: Question on the demos n.1

The responses show a clear majority, equal to 70%, of very or extremely positive responses.

Knowledge about Schenkerian Analysis

At this point we wanted to evaluate the adoption and methods of use of Schenkerian Analysis for melodic synthesis, asking the musicians if they know of such a theory.

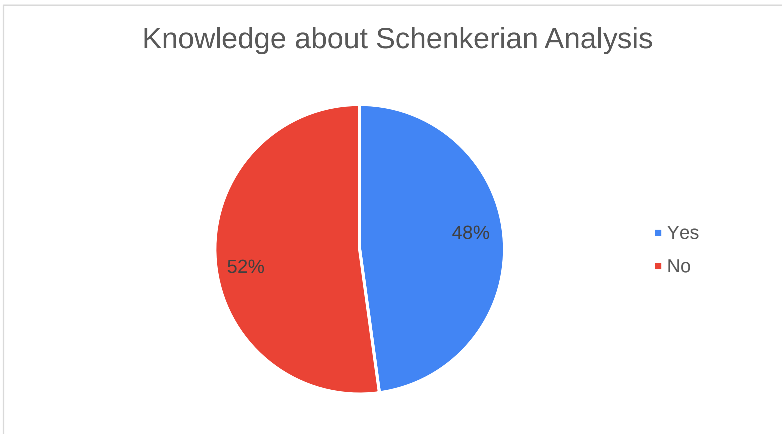

Figure 6.14: Question on the demos n.2

11 of the answers are affirmative, while 12 are negative. Only 3 of the musicians who claimed not to be composers were aware of this theory, while 5 composers were not.
Of these 5 musicians, 4 do not have a university degree but a music school diploma. The answers reflect the diffusion reality of the knowledge of Schenker's theory, nowadays known in the compositional field in high-cultural musical circles but not very widespread outside such contexts. This situation is however influenced by the local academic systems, which tend to stick to classical musical analysis.

Coherence of the synthesis approach

Since the process of melodic synthesis is a novelty presented in this thesis and it has been elaborated for the precise purpose of being adapted to the principles of cellular music, those who are familiar with Schenkerian analysis have therefore been asked for a judgment based on the ways in which it has been applied to this process.

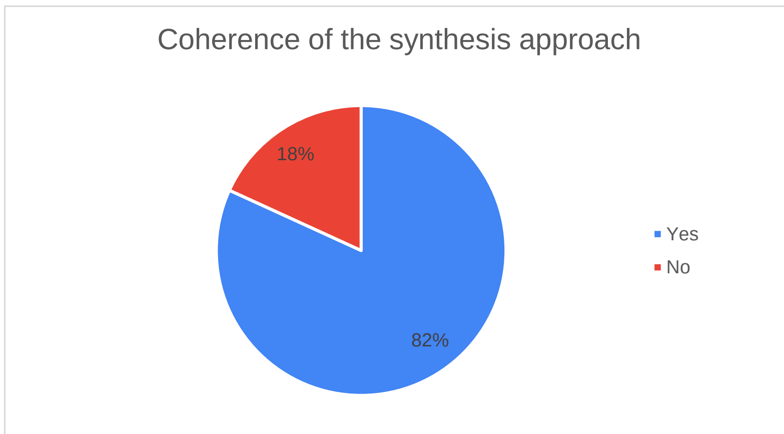

Figure 6.15: Question on the demos n.3

Of the 11 affirmative answers to the previous question, 9 have confirmed the coherence of such an approach, while only 2 are negative.

Use of Schenkerian Analysis in C.A.C

The last question of the questionnaire is aimed at verifying the widespreading and use of Schenkerian analysis in tools for assisted composition, asking the subjects who answered affirmatively to the second question if they knew any.

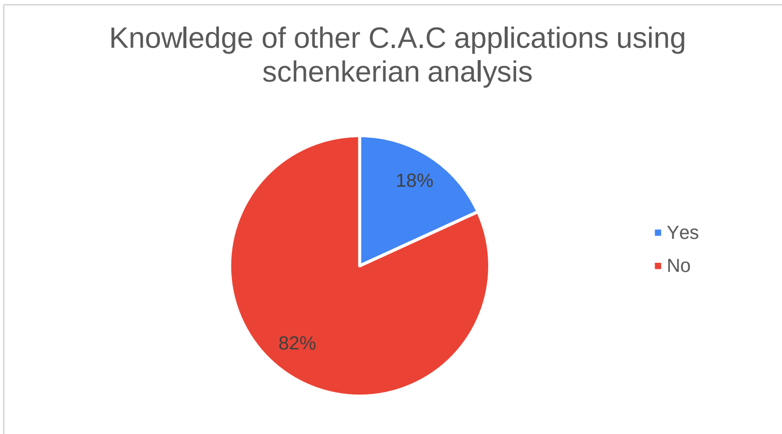

Figure 6.16: Question on the demos n.4

Of the 11 affirmative answers to the previous question, 9 are negative, while 2 are positive. The positive ones were therefore motivated by citing Lilypond[17], a music notation program that also includes that of Schenkerian analysis, although it does not allow computer-assisted composition.

6.2.5 Comments, Advices and Suggestions

At the end of the survey the participants were given the opportunity to express a personal comment, advice or suggestion for future developments in an open answer. A total of 11 responses were collected, of which here only some particularly noteworthy will be reported:

> ”Very interesting prototype, I find the idea of self-generative particle music very interesting and stimulating, and it is a theme that is very close to my heart. Personally I believe that the field of application in which this practice can give the most interesting results is synthesis (e.g.: concatenative and mosaicing).” (A. B.)

”It would be interesting to try to apply this technique to different musical genres to evaluate its impact and results. Even with genres that are not based on a cellular structure and therefore, on paper, they would not seem particularly suitable for the application of this technique.” (S. C.)

”I believe that could be used "intermediate" frequency systems that do not prefer chordal functions, cadences, phrase squaring, standard frequency arrangements etc., but which could generate an interesting result and not "difficult" listening: diatonic, pandiatonic, pentatonic, esaphonic systems. Drawing from alternative frequency systems could be very stimulating.” (F. V.)

”It could be interesting to develop the biological concept from prokaryote to eukaryote cell, expanding its structures and diversifying the roles of different cells as, for example, it occurs in an immune system. This could be achieved by keeping track of the cells considered "foreign" by the habitats, marking them as antigens to be suppressed would they reappear in certain quantities.” (M. M.)

”The system is very interesting and could be experimented even with acoustic instruments. A real-time performance, a kind of conducted improvisation, might be quite interesting.” (A. B.)

Chapter 7

Conclusions and further development

In this last chapter, conclusions on the principles of cellular music and their implementation are drawn from the answers to the survey. Next, possible ideas for future developments of the compositional paradigm and the general concept of cellular music are presented.

7.1 Achieved Results

From the survey responses collected emerges the actual novelty brought about by the compositional approach of cellular music. A clear majority of the interviewees showed a lot of interest in the described principles, believing that it has the potentialities necessary to constitute a complete compositional paradigm, capable of adapting to already existing musical genres or languages as well as to create new ones.

The system has been assessed as capable of exploiting artificial intelligence techniques well-established in literature in an innovative way, thus allowing exploratory artistic research without however constraining the freedom of expression of the musician, and on the contrary representing a versatile and tool, appreciable by professional artists with different musical backgrounds.

The implementation of the principles of cellular music into the (A)Live application has allowed the creation of original compositions with content recognizable according to the compositional criteria adopted, capable of alternating audio products belonging to different musical languages. The balanced combination of direct composition and the use of neural networks proved to be a good compromise between human control and the autonomy of the machine.

The principle of evolutionary music through the interaction of cells and habitats was evaluated very positively by the participants of the survey and, through the setting of different rules according to which such elements can influence each other, proves capable of being extended and applied to the most disparate musical fields.

The use of Schenkerian Analysis as an expedient for the synthesis of melodies starting from preexisting material represents a novelty in the field of computer-assisted composition, as it allows to algorithmically apply certain sets of rules, known a priori, in order to create sequences of sounds with constructive coherence. This analysis represents a powerful tool for algorithmic composition, which can be further explored and, with due adaptations, applied to different contexts.

7.2 Further developements

The very concept of a compositional paradigm as a musical framework within which different rules can be applied to build an original musical language leaves open the possibility for countless developments.

First of all, the concept can be duly extended to musical languages unrelated to tonality, atonality and microtonality, generating appropriate sets of rules and potentially deriving an even more effective use of the paradigm presented in this thesis in its most general sense.

Habitats are modeled as static regions in which cells move and interact with, but a possible development to give greater dynamism to a musical composition could be to create habitats capable of changing over time, following predetermined progressions or "mutated" by the amount and type of cells that have passed through them.

Another interesting development with regards to habitats could be the possibility for them to have irregular or fragmented forms, so that they can be detached from the timbral aspect of the cell's position in the two-dimensional space.

The acoustic space itself can be expanded to allow a diversification of the roles assumed by different melodic cells, for example by adding an additional dimension to the ecosystem. Cells arranged on different vertical planes can be subject to different fitness functions, evolutionary principles and types of interaction. It could be also considered inserting particular functions for the transition of cells or melodies from one floor to another, as well as regulating the interaction between floors, creating a sort of "cellular counterpoint" in which the different voices stick to the compositional paradigm presented here.

More articulated functions drawn from cellular behavior can be implemented and duly set up to allow for better artistic exploration or to refine existing techniques. For example, it can be introduced the possibility for the system to "immunize itself" against cells with characteristics particularly unsuitable for living in the ecosystem, keeping them in memory and eliminating any similar cells to have better control of the active musical material.

The functions of musical synthesis in the case of tonal fusion are limited to modeling the melodic aspects of Schenkerian Analysis, but this theory can be further translated into rules for the algorithmic creation of musical objects of greater complexity. This approach can be extrapolated from the context of cellular music and be applied more generally in different fields of algorithmic composition and beyond.

The application program (A)Live can and will be further improved and strengthened, and will be the subject of a broader investigation, carried out through direct testing of the application, which hasn't been possible to do in the current situation.

The implementation presented, currently "limited" to the synthesis and interaction of melodies, can be further extended through the insertion of harmonic components, for example a particular type of "vertical fusion" between melodies could be introduced, which allows two sequences of notes to join in a sequence of bichords or chords.

Furthermore, the concept of cellular music can be extended beyond computer-assisted composition, and become an artistic tool applicable to different musical situations. For example, one could think of a social interaction platform in which different people are associated with melodic cells, and whose movement or interaction influences a musical or visual output, creating an interesting artistic effect.

The possibilities of development and application of the principles of cellular music, with the necessary adaptations, are countless.

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