THE BARTLETT SCHOOL OF ARCHITECTURE

M.Arch Design for Performance and Interaction

DESIGN THESIS

# Musical Emergence
A study of self-organisation and disruption in systems of distributed performers

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**Abstract**

This thesis explores the parallel between self-organisation in non-human complex systems and the process of improvisation in musical ensembles. Both phenomena illustrate the concept of emergence, which can be defined by the appearance of a structure at the scale of the system, that cannot be predicted from the behaviour of its individual components. Swarms and other self-organising systems such as cellular automata offer rich material that could be used in the composition of music, as their behaviour happen to be usually based on a set of simple rules. The goal of this thesis is to draw from the analysis of several complex systems the conditions that allow emergence to happen. The hypotheses stated and analysed in this thesis are being implemented in a research project developed at the Interactive Architecture Lab : *Sound Insects*.

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# 1 Introduction

Ensemble improvisation in music is a fascinating phenomenon to witness. Musicians improvising are able to understand the dynamics of the group and can adapt their contribution in real time in order to guarantee the stability of the live composition while at the same time allowing it to evolve. Interestingly, this kind of behaviour echoes the phenomenon of emergence in self-organising systems such as swarms (Blackwell T., 2002) or cellular automata, in which a sustained structure appears at the macroscopic scale of the system (Blackwell T. and Young M., 2004).

*"At one level, improvisation can be compared with the ultimate otherness of an ant colony or hive of bees." (Toop D., 2002)*

In a way, musical group improvisation is about trying to create order while dealing with potential disruption at every instant of the performance. This is achieved using peer to peer listening, much like birds that constantly modify their trajectory depending on their neighbours position to enable the group to quickly react to any environmental change.

Understanding more clearly the mechanisms behind improvisation and emergence is very appealing from an artistic perspective. It could lead to new composition techniques and unexplored musical outcomes, for instance by using swarms simulations to generate harmonious and ever-changing musical events or by giving new sets of rules to improvising musicians.

This research project aims to answer the following question : **what are the sufficient conditions for the emergence of music in a system of distributed performers?**

# 2 Methodology

## 2.1 Hypotheses

As mentioned above, improvisation in groups of musicians and other self-organising systems shows two determining behaviours :
1. Their ability to create order at the scale of the system
2. Their ability to generate disorder and react to it

The following diagram (Figure 1) is a graphical representation of the hypotheses stated above. Throughout the performance, the level of order of the musical creation oscillates from periods of structuration (1) when the system self-organises and periods of de-structuration (2) when a disruption modifies the stability of the system.

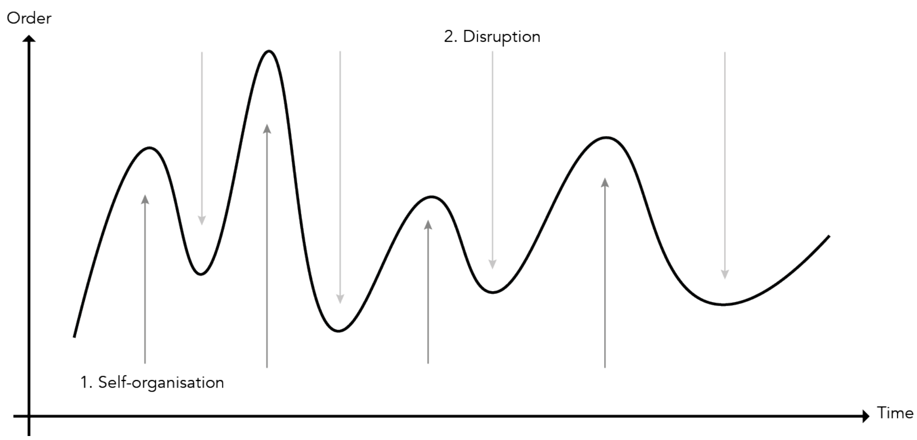


Figure 1: Evolution of order in musical improvisation

The first chapter of the thesis will focus on defining the notion of order in music and identifying the sufficient conditions that enable the creation of order in several self-organising systems. The second chapter will go on to study musical evolution by looking at the origins of disruption and highlighting the conditions that are necessary in the implementation of a system for it to generate disorder and react to it.

## 2.2 Goal of the study

This thesis compares the artistic components of self-organisation with those of scientific origin in order to draw conclusions about the core constitutive elements of musical emergence. The goal of the next two chapters is to define a list of hypotheses on the nature of improvising collaborative performers. They aim to answer questions such as: What rules do performers follow? What disruption can affect them? How do they interact with each other and with their environment? If a set of sufficient conditions for the emergence of music can be established, then it may be possible to implement them in a system of distributed machines.

*Sound Insects* is an immersive interactive sound installation composed of multiple identical electronic modules that interact with each other through audio feedback. As shown on the following diagram (Figure 2) and on the picture of the installation (Figure 3), the system features a set of modules distributed in an environment and interacting with each other when they happen to be within hearing distance. The goal of the project is to explore how trivial rules of interaction applied to a system of independent modules can lead to musical emergence. This project is designed to be both a performative art installation as well as a research tool that could lead to unexplored musical paths and new instrumental interactions. Two prototypes of the project are studied in this thesis: *Rhythmic Sound Insects* (Prototype 1) and *Harmonic Sound Insects* (Prototype 2).

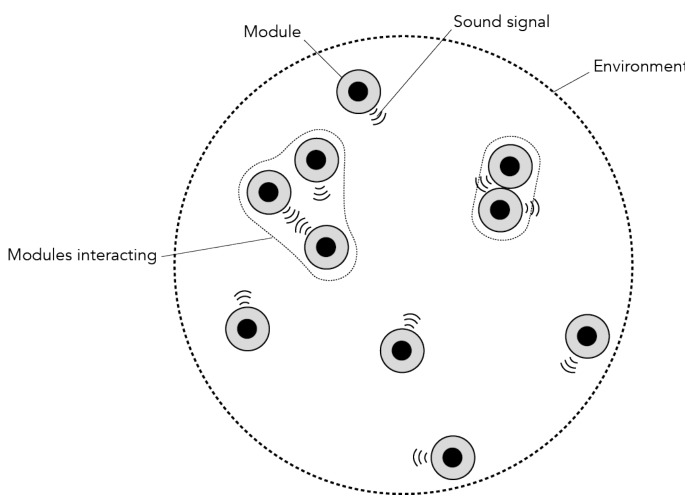


Figure 2: *Sound Insects*, Functional Diagram

The contextual research carried on hereafter will serve as a tool to understand what type of algorithm, physical features and surrounding environment should be applied to these trivial modules in order for them to generate music.

Figure 3: *Rhythmic Sound Insects*, Marguerite Tricaud (2018)

# 3 Order

## 3.1 A first definition of order : entropy

Entropy has been used by researchers such as Meyer (Meyer B., 1957) as well as composers such as Stockhausen (Eco U.,1962) or Ianis Xenakis (Xenakis I., 1971) to understand or create music. Cybernetician Max Bense believed that "entropy could be normatively applied to the production of aesthetic products, what he called 'the programming of beauty' " (Patteson T., 2012).

The entropy of a system, often described as its level of disorder, is formally defined in thermodynamics as a quantity dependent of the number of different microscopic configurations that the system can be in. When a system shows an organised behaviour, the entropy of the system decreases.

This can be illustrated by the simple example of a group of musicians following basic rules. If the musicians are asked to play the same note, there is only one option per musician. The number of possible configurations of the system is equal to one, and this is the lowest state of entropy that the system can be in. As one can imagine, a group playing only one note note will sound ordered and stable. If one of these musicians is allowed to play any other note, then the level of disorder will increase. If a pianist is given a choice between any of their 88 keys, then the system can be in 88 different configurations. The level of disorder of the system rises, but is still relatively low compared to a situation where two pianists amongst a group are allowed to play any note (in which case the number of possible configurations is $88^2 = 7744$).

Greg Cox points out the direct correlation between the evolution of tension in a musical piece and its level of entropy, saying "an authentic cadence is a point of repose and thus should be correlated with lower entropy. A dramatic climax should be correlated with a high value of entropy (a local maximum) as it represents a large amount of tension." (Cox G., 2010).

The entropy of a musical system also correlates to the probability of any given musical event happening at every instant of the performance. Meyer defines musical styles as complex systems of probabilities. He explains that in the tonal harmonic system of Western music, there is a probabilistic relationship between one chord and the chord that will follow: "the tonic chord is most often followed by the dominant, frequently by the subdominant, sometimes by the submedian, and so forth." (Meyer B., 1957). A musical performance can be seen from a listener's point of view as a probabilistic tree. As shown in Figure 4, at each moment of the performance, the performer has the choice between all the notes that they can physically generate (events A, B or C), but is highly susceptible to play the note that has the highest probability (for example A if P(A)>P(B) and P(A)>P(B)). The probability of each note depends on the previous notes played, the genre, the instructions of the composer, etc. As stated by Greg Cox, the higher the probability is for a musical event to happen, the lower its entropy (and tension) will be (Cox G., 2010).

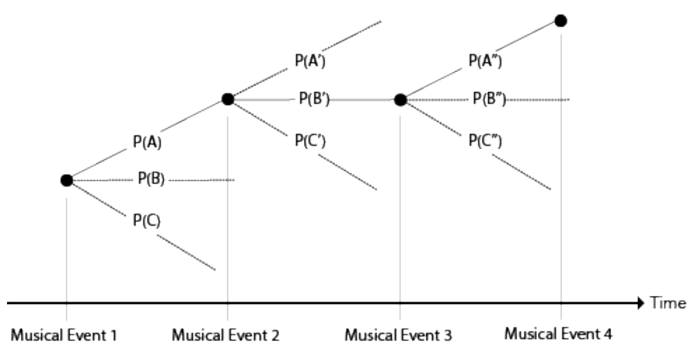


Figure 4: Probabilistic tree of musical events in an improvised performance

Todd Hostager provides a similar graphical notation to describe the musical path chosen by performers in jazz improvisation. On the following diagram (Figure 5), he represents the musical possibilities by a tree of which the branches correspond to the potential paths offered to the performers. The main branch, highlighted in bold, shows the path taken. He explains that the center of the tree, at the origin of the different paths, represents the "shared information regarding jazz theory, song structure, behavioural norms and communicative codes" (Hostager T., 1988).

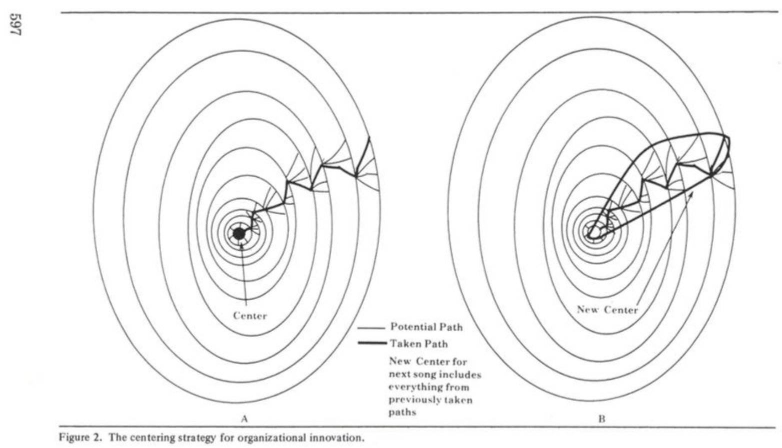


Figure 5: *The centering strategy for organizational innovation*, in "Jazz as a Process of Organizational Innovation" (Hostager T., 1988)

The examples above demonstrate that the level of order of a musical performance is defined by a set of constraints or rules that orient the musicians' choices at each branch of the probabilistic tree.

## 3.2 Rules

Improvisation and pre-written music can be both considered as composition. An improvisation is a composition played immediately, whereas pre-written music is played subsequently (Rosenboom D., 1996). Their main difference is that rules in pre-written music dictate the outcome of the performance by defining the exact behaviour of the performers, while ensemble improvisation rules orient the behaviour of each performers but cannot predict the behaviour of the system as a whole. In any type of musical composition (written or improvised music), rules can be defined by both physical and abstract constraints.

### 3.2.1 Physical constraints

In music, the rules applied to the system are not only defined by an exterior individual (composer) but also come from physical constraints such as the design of the instrument. For instance, a piano has a restrained set of discrete notes that can be played, whereas a cello has a continuous range of possible notes. The physicality of the instrument does not only affect the number of frequencies that can be generated but also the length of the notes, their timbre, etc. These physical constraints mostly apply to acoustic or analog electronic instrument, as digital instruments are practically not affected by physical restrictions of sound production (Tricaud M., 2018). Due to its lack of physical constraints, computer generated music offers high levels of entropy. It therefore needs stronger abstract constraints to lower the level of disorder to a stable musical state.

### 3.2.2 Abstract constraints

In opposition to physical constraints that are defined by nature, abstract constraints come from socially constructed laws such as the musical genre or any other subjective decisions of the artist.

*Musical genre*

As mentioned by Meyer, all musical genres are defined by "rules of musical grammar and syntax found in textbooks on harmony, counterpoint and theory in general" (Meyer B., 1957). This is what enables musicians and composers to create order, and what enables listeners to identify it. As proposed earlier on, the level of order of a musical event is identified in comparison to what is expected by the listener. This expectation relies on centuries of composition that trained our ears to specific musical norms. When a perfect cadence terminates a piece of baroque music, every note seems structured and perfectly ordered: the listener's ear is trained to western classical music and expects the musical resolution. Rules of musical grammar and syntax are not only used in pre-written music but are also extremely present in improvised jazz. Bastien and Hostager divide these conventions into musical structures (the formal rules of jazz theory) and social practices (Einsenberg E., 1990).

*Communication rules*

Social practices are fundamental in improvisation because they enable the communication of musical information (Meyer B., 1957). This is particularly relevant in ensemble situations, where the set of rules defined by the genre allows the musicians to understand the musical behaviour of the group. In this way, they are able to adapt their playing whereby guaranteeing the stability of the emergent creation. In a standard jazz improvisation, such abstract rules are usually defined by habit and practice. Eisenberg divides these into behavioural and communicative norms. Behavioural codes are used as guidelines by each musician during the performance (for example each musician gets a chance to solo at some point in the performance), and communicative codes enable musicians to signal changes to the other members of the group (for example using hand gestures to indicate a change in dynamics or tempo). These communication rules are necessary to "allow players to coordinate actions whilst inviting autonomous expression" (Barrett J. F., 2000).

*Other abstract constraints*

In the mid 20th century, a group of experimental musicians broke out of cultural norms to explore different sets of constraints. Composers such as Steve Reich and John Cage began to generate new musical outcomes in this way, playing with new abstract rules in their works. From this same artistic movement, Robert Ashley's composition *She Was A Visitor* is a good example of ensemble improvisation where a set of abstract rules is given to a group of performers as a way to generate unexpected but organised results (Figure 6).

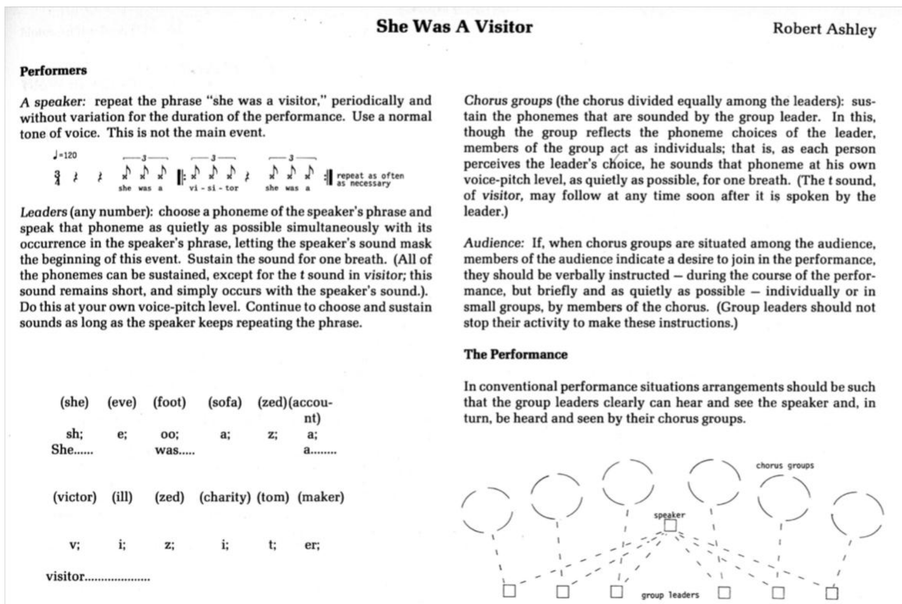


Figure 6: Performance rules for *She Was A Visitor*, Robert Ashley (1967)

As shown in Figure 6, the piece clearly states what each performer is meant to do in relationship to the other members of the system. For example, the group leaders respond to the main speaker by choosing a phoneme to repeat, while the chorus groups react to their designated group leader by sustaining the phoneme chosen. These simple rules of interaction are sufficient to generate an unplanned but ordered musical outcome.

It appears from the previous examples that the abstract constraints dictated by the genre or by the artist serve both as a guide for each performer and as a communication tool between multiple performers; both are necessary conditions to maintain order in the system. Barrett provides an accurate summary of those rules: " individuals have personal freedom to take initiatives and operate on their own authority (their musical imagination), guided by the constraints of the task, the conventions of practice and the enactments of other players" (Barrett J. F., 2000).

## 3.3 Emergence

From the definition of order and the analysis of composition rules can be concluded that when all individual entities of a system follow a common set of rules, a sustained structure appears at the macroscopic scale of the system (Blackwell T. and Young M., 2004). This phenomenon also called emergence is observed in complex systems when "new properties and behaviours emerge that are not contained in the essence of the constituent elements, or able to be predicted from a knowledge of initial conditions" (Mason M., 2008)(Tussey D., 2005)

### 3.3.1 Cellular Automata

A Cellular Automaton (CA) is a compelling example of the phenomenon of emergence. In a cellular automaton, a set of basic rules is applied to each cell of the system individually, constraining them to respond to their surroundings cells in a specific way. Each cell can be considered as a trivial machine (Gage S., 2006), which means that the same input will always trigger the same output.

In an elementary one-dimensional cellular automaton, the state of each cell only depends on the state of the three adjacent cells situated on the row above. A cell can be in only two states: black or white. There are therefore eight configurations possible for a group of three cells, as shown below at the top of Figure 7. For each of these configurations, the rule of the CA attributes one outcome that defines the state of the new cell. For example, the set of rules shown on Figure 7 states that when three adjacent cells are black, the new cell will be white.

Each elementary CA starts with one black cell in the middle of the top row, and, at each time frame, a new row is generated using the rules of the CA applied to the previous row. The following figure is an example of one such set of rule.

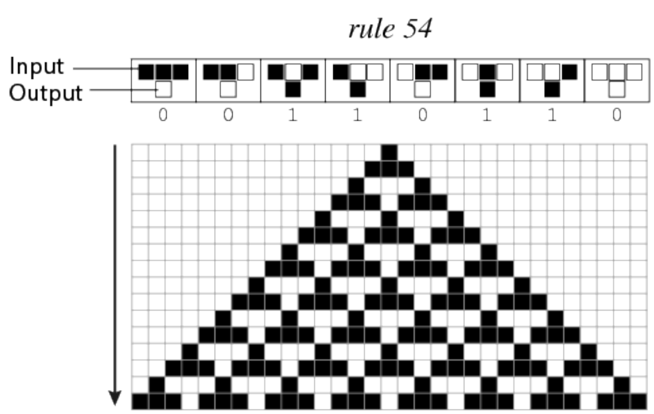


Figure 7: Cellular Automata, rule n°54

The figures presented hereafter (Figure 8) show different scenarios of elementary cellular automata. What can be observed is that different sets of simple rules will generate different emergent graphical patterns.

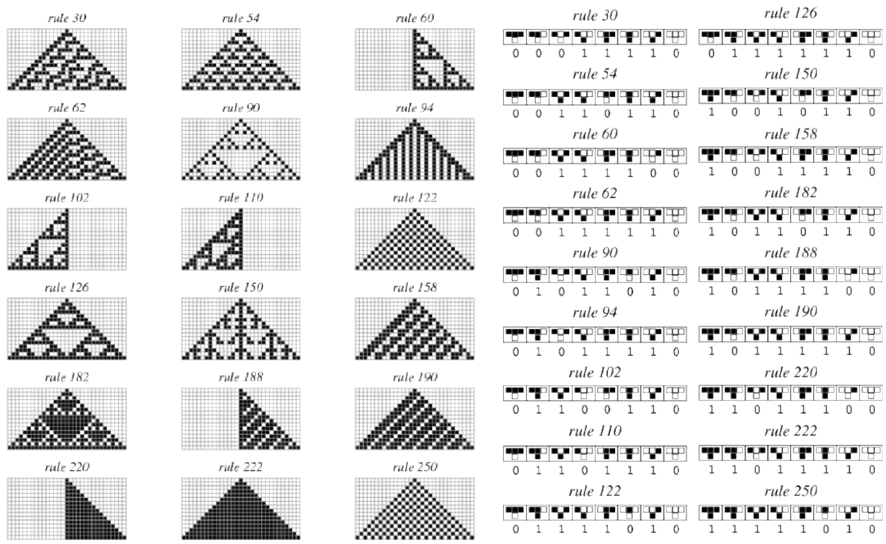


Figure 8: Examples of Cellular Automata and their associated rules

The Game of Life is a two-dimensional cellular automaton created by mathematician John Horton Conway that generates an emergent behaviour imitating the growth pattern of a colony of living organisms. It is helpful in understanding the idea of emergence and how it can relate to a performative musical system. The concept is similar to the elementary CA except that instead of reacting to the three previous cells, each cell now reacts to the state of its eight adjacent cells, which changes at each time frame (Miranda E. R., 2003). The particularity of the Game of Life is that there is one specific set of four rules that enables the emergence of a life-like behaviour :

" a) Birth: A cell that is dead (white) at time t becomes alive (black) at time t + 1 if exactly three of its neighbours are alive at time t;
b) Death by overcrowding: A cell that is alive at time t will die at time t + 1 if four or more of its neighbours are alive at time t;
c) Death by exposure: A cell that is alive at time t will die at time t + 1 if it has one or none live neighbours at time t;
d) Survival: A cell that is alive at time t will remain alive at time t + 1 only if it has either two or three live neighbours at time t." (Miranda E. R., 2003)

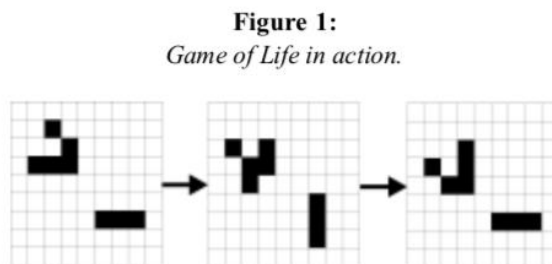


Figure 9: Evolution of cells in the Game of Life

Depending on the initial conditions of the CA (what cells are set as alive and what cells are set as dead at t=0), the system will show different dynamic patterns.

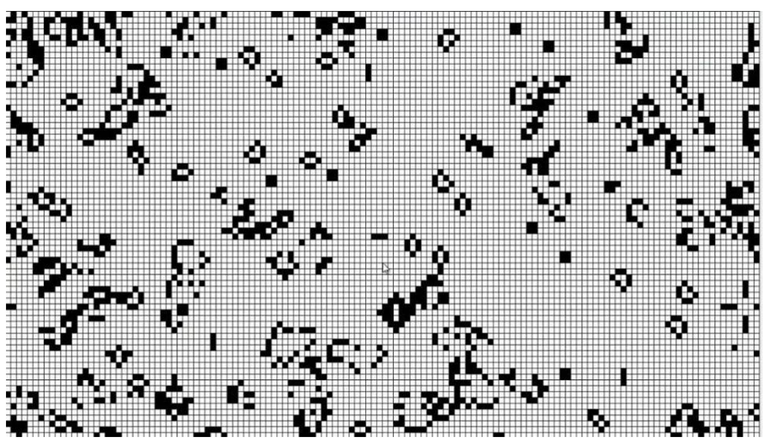

Figure 10: Graphical pattern generated by the Game of Life

This means that one trivial algorithm dictating the behaviour of a cell in relationship to its direct neighbours combined with a choice of initial conditions are sufficient conditions to enable self-organisation in a system of distributed performers.

Self-organisation can therefore by achieved in a system that possesses:

Condition 1. A trivial algorithm dictating the behaviour of an individual in relationship to its direct neighbours

Condition 2. An initial set of conditions that are able to impact the outcome of the performance

### 3.3.2 Performative Emergence

The concept of emergence has been applied in the development of new composition softwares and techniques (Miranda E. R., 2003), (Xenakis, 1971), but has also been used in a more sociological approach in the study of musical and theatrical improvisation. Sawyer uses the concept of "the emergent" to describe the creation that appears from the contribution of all participants and which evolves throughout time by being fed and filtered by individual decisions while also following up on its previous self (Sawyer R. K., 1995). This is represented by the following diagram (Figure 11) that shows the looping mechanism by which the members of the improvising group find, propose and filter new creative material to enrich the emergent.

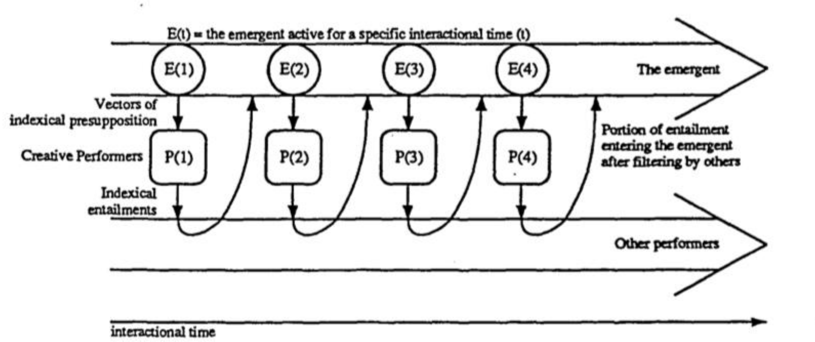


Figure 11: *Synchronic (improvisational) interaction*, (Sawyer R. K., 1995).

He describes the emergent as being a "constraining force" acting back on the performers, creating this feedback loop between microscopic and macroscopic level of the system (Sawyer R. K., 1996). At every moment, the decision of a performer will orientate the improvisation in an even more precise path. Sawyer gives the example of a short improvisation in theatre where two actors evolve, in the time-frame of a few sentences, from an infinity of possible configurations (when no one has said or done anything), to a more constrained situation where one actor is a bus driver and the other is a passenger. In this specific example, where the actors settle the situation in which they will develop the performance, each decision lowers the entropy of the system and brings it to a more ordered state. For example, when the first actor decides to sit and mimic a driver, the number of possible configurations drops from infinite (being anywhere) to being in a vehicle, and when the second actor comes in and stands next to the driver, looking for something in his pocket, the entropy drops again as the situation evolves from being in any vehicle to being in a bus.

The performing system is therefore constrained by two main entities: the general rules defined prior to the performance, which are absolute as they do not depend on the performance itself, and the emergent rules that depend only on the performance (Figure 12). This statement is also valid in musical improvisation, where the absolute rules are defined before the beginning of the performance (by constraints stated by the musical genre, the social norms of musical interaction and the physicality of the instruments), and the emergent rules are created during the improvisation (by the choices of the musicians).

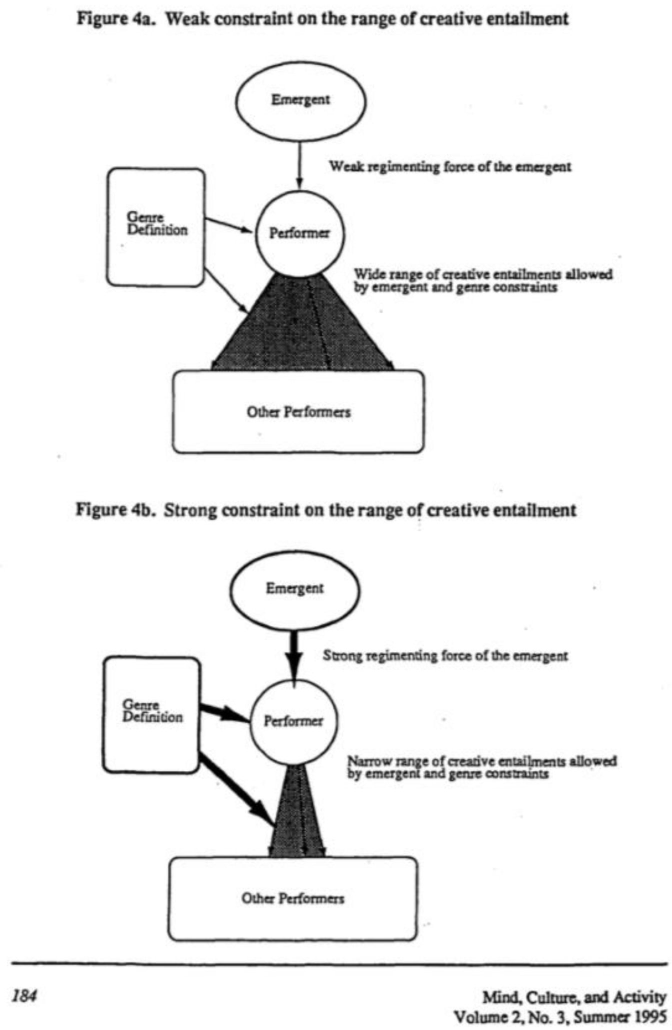


Figure 12: *Constraints on the range of creative entailments*, (Sawyer R. K., 1995).

## 3.4 Feedback

Ruairi Glynn's *Performative Ecologies* (Figure 13) also explores this idea of feedback from the emergent to the system. *Performative Ecologies* is a community of autonomous dancing modules that each sense visitor's reactions to their movement. Each module shares its individual experience with the other modules, allowing the system as a whole to evolve and better attract people's attention. The emergent dance arising from the system is acting back on itself through the reaction of the audience, generating each time a unique, unexpected performance. The result of this is that both the audience and the performers have a responsibility in the creation of the emergent, as they can consciously or unconsciously reinforce certain patterns.

Figure 13: *Performative Ecologies* ,Ruairi Glynn (2007).

This reinforcement behaviour is considered as one of the core properties of swarm intelligence, and is most commonly referred to as positive feedback. David Borgo gives a clear description of positive feedback by comparing musical improvisation to insect swarms.

*"Through positive feedback musicians not only develop their own ideas from a kernel of inspiration, but they also work together to support the ideas of others and the evolving ensemble sound. They "recruit" others to support or sustain their own developments, or they may choose to "reinforce" the creative direction of others instead. Similar to the ways in which information about the best food source or the shortest path can be compounded among a swarm of bees or a*

*colony of ants, positive feedback increases the ability of an improvising group to follow the more "promising" of many concurrent ideas being pursued by various members."* (Borgo D., 2006)

It appears, from the examples of performative improvising systems studied in this thesis, that emergence can appear only if it is sustained by an entity responsible for its reinforcement. This entity can be either the performers, the audience or both. Defining who in the system is responsible for the judgement of the emergent and its reinforcement will play an important role in the way the system creates order. This brings a third necessary condition for the emergence of order in a system of distributed performers :

Condition 3. An entity responsible for the reinforcement of the emergent

## 3.5 Conclusion : patterns

What can be concluded from the case studies discussed above is that a system is perceived as generating order when it creates a pattern. This can be defined as the repetition of a similar event in time and/or space. An observer or listener identifies order when what is presented to them aligns with what they expect. Tim Blackwell defines music as "a pattern of sounds in time" (Blackwell T., 2007), and Meyer goes as far a saying that "our whole mental existence is built around our expectations as to the normal (probable) continuity of events. We "expect" to get up Monday morning, to eat breakfast, to see that the children get to school, to go to the office, and so forth" (Meyer L. B., 1957). The repetition of an event happening in any time or space frame falls into the definition of a pattern. Some examples include: the repetition of a series of musical units during a time-frame of seconds in a musical piece, similar musical syntax used over years by difference composers of the same genre, repeating shapes in the spatially-framed output of a CA or the similar movements of kinetic objects that are sharing their knowledge in a spatial-frame of meters.

In this chapter, three necessary conditions for the generation of patterns in a distributed system of musical performers were identified :

Condition 1. A set of rules dictating the behaviour of an individual performer in response to its immediate neighbours

Condition 2. A set of initial conditions that will orientate the direction of the performance

Condition 3. An entity responsible for the reinforcement of the emergent

# 4 Disorder

## 4.1 The necessity of disorder : novelty

*" A compromise between order and disorder, improvisation is a negotiation between codes and their pleasurable dismantling"* (Corbett J., 1995)

Creating order and emergent patterns is not the only aim of music (both written and improvised). The appearance of order necessarily indicates prior chaos, and this evolution to stability is satisfying to hear. However, there is also a satisfaction in moving from stability to chaos: the appearance of novelty. Most of the research on aesthetics, music and complexity theory agrees that creative processes take place in this unstable equilibrium state, at the edge between order and chaos (Birkin G., 2010) (Barrett J. F. , 2000) (Tussey D., 2005) (Blackwell T., 2007). The edge of chaos is a fertile ground for creation: because of the instability of the system, "tiny changes can amplify and alter the state of the system, escalating into qualitatively different patterns" (Barrett J. F. , 2000).

In their study of self-organising systems, Bonabeau, Théraulaz, and Dorigo from Santa Fe Institute set a degree of randomness or error as one of the four key conditions for the appearance of emergence, alongside positive feedback, negative feedback and multiple interactions of multiple entities (Borgo D., 2006). Borgo and Blackwell agree that a certain degree of randomness is crucial to produce fluctuations enabling novel situations to happen (Blackwell T., 2007)(Borgo D., 2006).

Error is also inherent to the process of musical improvisation and specifically in jazz : " If there is no mistake it is a mistake" (Zwerin M., 1983). Unexpected occurrences "provide both source material and inspiration for individuals and groups to explore new sonic territory, musical techniques and interactive strategies" (Borgo D., 2006).

It is therefore evident thats a source of disorder is a necessary condition for musical emergence in self-organising systems.

Condition 4. A source of disorder

## 4.2 The origin of disorder

In a group of musicians improvising, the performers themselves are the agents responsible for the appearance of novelty. As mentioned earlier, either error or voluntary changes both work as sources of musical transformation. Musicians usually voluntarily disrupt the stability of the emergent creation when they feel the need to evolve to a different state. David Borgo explains that "many improvisers, if they sense that all of the participants are following each other too carefully, will "go against the grain" or "forge out on their own" into new sonic territory; in other words, they will defy the logic of the hive mind." (Borgo D., 2006). He even goes deeper in the analysis of the origin of novelty by pointing out the "distinction between an ideation stage, in which the non-conscious brain produces novelty through divergent thinking, and an evaluation stage, in which the conscious mind decides which new ideas are coherent with the creative domain" (Borgo D., 2006). This last statement questions the concept of mistake in musical improvisation, which should imply a discrepancy between intention and action (Barrett J. F., 1998), but which could also be considered, with Borgo's approach, as a voluntary but simply non-conscious process.

In natural self-organising systems such as bird flocks, disorder is usually not generated voluntarily by one individual of the group but comes from external events. The environment in which natural systems perform offers ever-changing, uncertain and complex sources of disorder (Blackwell T., Young M., 2004). Wind or natural obstacles appear as completely random events from the individuals' perspective and are therefore highly unpredictable. Conversely, musicians in a jazz ensemble are more likely to disrupt order in a controlled manner rather than by pure random mistakes.

Logically, the degree of novelty is higher when the predictability of an event is lower, which implies that external sources of disorder provide a stronger potentiality for transformation. Mason suggests that "a complex system showing emergence can be defined by the impossibility to predict its behaviour" (Mason M., 2014). Moreover, a non-mutational system (a system that does not generate inner disruptions) provides an easier approach for a researcher to study the behaviour of the system in reaction to its environment without having to analyse unexpected individual behaviour of its members.

Cellular automata, as mentioned earlier, are compelling examples of a non-mutational system, as the cells always react identically to the same conditions. This means that the diversity of patterns observed only depends on the environmental influence which is decided by the set of initial conditions chosen by the CA's designer.

In a way, environmental influence in a physical setting (wind, rain, obstacles, sound, etc) can be considered as an ever-changing set of initial conditions. At every instant of the performance, individuals react to the conditions set by the environment in which they evolve, until a disruption comes to re-configure those settings.

This gives a new definition to the second condition for musical emergence in a system of distributed performers discussed above. Condition 4 (a source of disorder) can now include Condition 2 (a set of initial conditions).

Condition 1. A set of rules dictating the behaviour of an individual performer in response to its surroundings

Condition 2. An external source of disorder

Condition 3. An entity responsible for the reinforcement of the emergent '

## 4.3 Defining the nature of the environment

In most academic research on swarming systems applied to musical creation, a digitally simulated external environment is used to produce fluctuating activations impacting on individual agents (Beyls P., 2007). Softwares such as SWAR-

MUSIC (Blackwell and Bentley, 2002) or CAMUS (Miranda E. R., 2003) are computer-generated swarming systems where no individuals nor environment possess physical bodies. Digital simulations are often preferred by researchers and composers over physical systems because they are faster, cheaper and easier to implement and they offer a holistic control of the system.

Some artists, however, defend analog media as a better tool to generate disorder. Musician and cybernetician Roland Kaynes considered embodied systems as aesthetically superior to digital components (Patteson T., 2012), because of the unexpectedness of fluctuations that they offer.

The Cybernetic Serendipity exhibition in 1968 gathered a profusion of work from the same artistic movement exploring the potentiality of analog randomness as a powerful aesthetic tool. The *Colloquy of Mobile* (Figure 14), an installation from cybernetician Gordon Pask that was presented at the Cybernetic Serendipity exhibition, illustrates how a system of trivial, embodied, distributed performers can show an emergent behaviour when confronted to the randomness of an analog environment. The *Colloquy of Mobile* is a system of moving light reflectors and generators communicating with each other via light beams (Haque U., 2007).

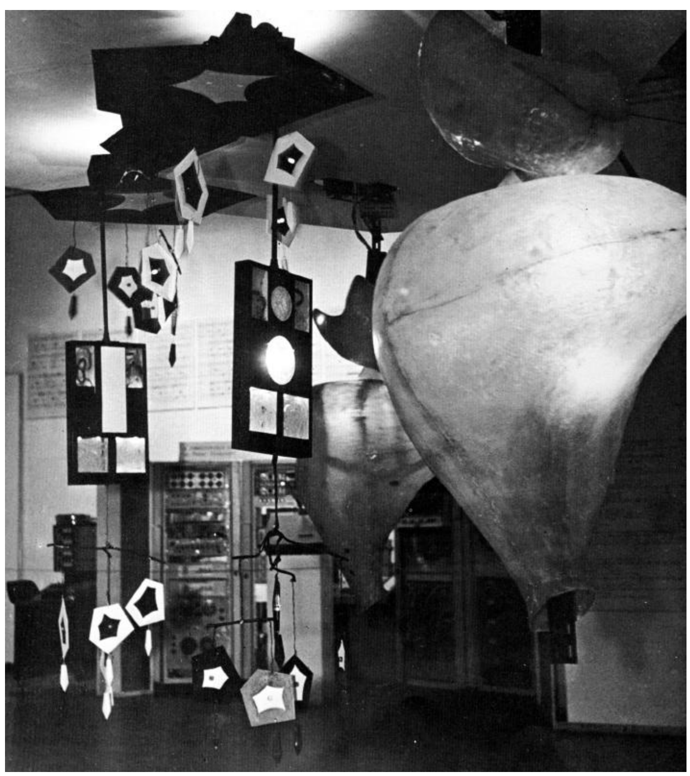

Figure 14: *Colloquy of Mobiles*, Gordon Pask (1968)

As the performers possess a physical body and use an analog media to communicate, the system is highly susceptible to disruptions such as people blocking the pathways of light (Haque U., 2007), or unpredictable reflections of light generated by the random rotation of the mobiles.

Embodied performers communicating through analog media provide a rich source of disruption. They also encourage audiences to interact with the system by playing the role of an environmental influencer in the emergence of musical performance.

## 4.4 Conclusion

This chapter has introduced an important condition for the generation of music in self-organising systems: the need for a disruptive entity to break stability in order for the musical performance to evolve. Analog environments are rich in disruption yet keep individual behaviours trivial, and as such they are ideal settings for the evolution of self-organising systems. This last statement can be translated in the set of conditions by an adjustment of Condition 2 :

Condition 2. An analog environment as source of disorder

# 5 *Sound Insects*

The study of self-organising systems in nature and in human performances presented in the last two chapters has brought up three sufficient conditions that should enable the generation and evolution of musical patterns in a system of distributed performers.

Condition 1. A set of trivial rules dictating the behaviour of individual performers in response to their surroundings
Condition 2. An analog environment as source of disorder
Condition 3. An entity responsible for the reinforcement of musical emergence

It therefore stands that if the above three conditions are fulfilled, then musical emergence will occur. The following chapter explains how the conditions have been implemented in *Sound Insects*, an interactive sound installation designed and built at the Interactive Architecture Lab, UCL.

## 5.1 Condition 1 : A set of rules dictating the behaviour of individual performers in response to their surroundings

### 5.1.1 Prototype 1 : *Rhythmic Sound Insects*

*Physical Rules*

In Rhythmic Sound Insects (Prototype 1), each module features a microphone and a speaker, and therefore can only communicate with its environment through sound. The power of the speaker and the sensitivity of the microphone are physical constraints that condition the interaction with other members of the system.

As the sound is produced digitally in the "brain" (arduino) of the module, almost any frequency can be generated. However, the choice of the chip used for the detection and synthesis of sound is a determining constraint as it has limited physical possibilities in terms of signal processing. In the first prototype of Sound Insects, an Arduino Pro Mini has been used to detect and generate sound. Because of the restrained processing power of this board, it is nearly impossible to get a stable frequency detection of external sounds, therefore only sound intensity can be used as an input.

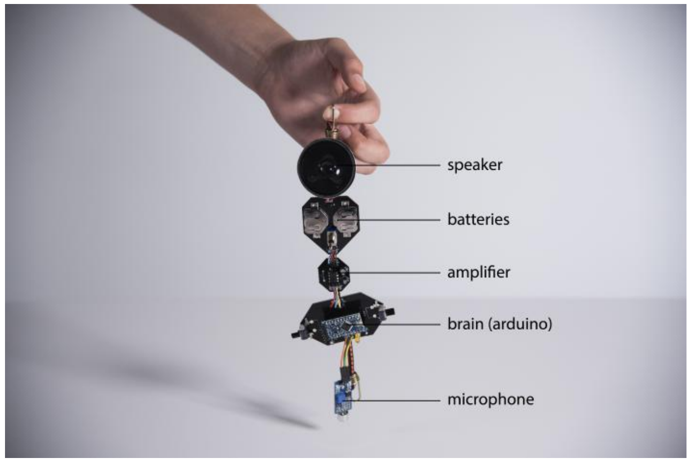


Figure 15: *Rhythmic Sound Insect*, Marguerite Tricaud (2018)

*Abstract Rules*

Due to the restrained physical possibilities of the first prototype, the rules of interaction are based on sound intensity as a trigger and delay as a reaction, as a way to generate rhythmic patterns. The behaviour of each module is very simple: every time a module detects a sound, it will wait for a specific time delay (chosen by the person interacting with the modules), and will then generate a beat (Figure 16).

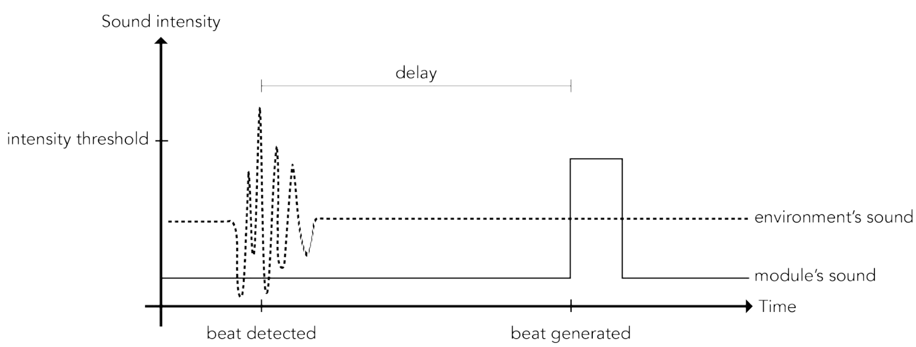


Figure 16: Interaction behaviour for a module of *Rhythmic Sound Insect*

If two modules are close enough to detect each other, they will enter a rhythmic loop, as shown in Figure 17.

Rhythmic patterns created will vary depending on the number of modules that are within hearing distance and the delay set for each module.

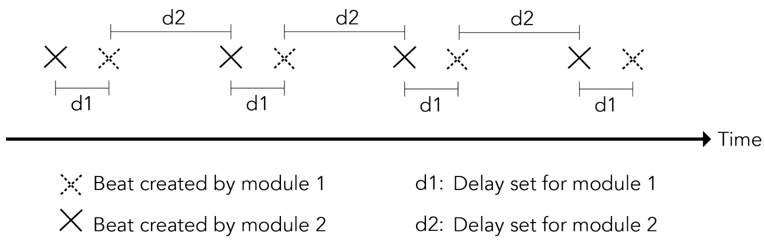


Figure 17: Rhythmic loop generated by two modules of *Rhythmic Sound Insect*

### 5.1.2 Prototype 2 : *Harmonic Sound Insects*

*Physical Rules*

The physical restrictions of Prototype 1 significantly limited the potentiality of musical emergence of the system. To be able to use sound frequency as the main communication tool between the modules, a stronger processor is required. In Prototype 2, which is still under development, smartphones are used instead of Arduinos, enabling pitch detection as well as sine wave synthesis.

*Abstract Rules*

When a frequency is detected by a module, it will calculate the interval between its own frequency and the frequency detected, then modify its frequency until that interval reaches a musical harmonic interval to be defined (Figure 18).

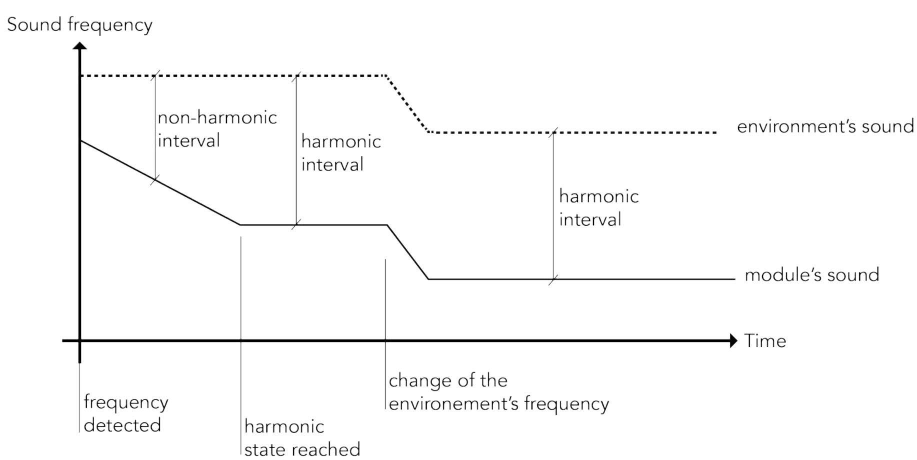


Figure 18: Interaction behaviour for a module of *Harmonic Sound Insect*

Different sets of harmonic rules can be implemented. The first set of rules implemented in the simulation of Harmonic Sound Insects defines three consonant intervals to be reached, based on the western musical theory :

- Unison (0 semitones difference between the two notes)
- Perfect fourth (5 semitones)
- Perfect fifth (7 semitones)

This set of rules was chosen so that all the intervals between adjacent notes are perfect fourths or fifths, which will always sound stable. This means that detecting and reacting to only one other module is a sufficient condition for the emergence of harmony.

The diagram presented below (Figure 19) shows a simulation of harmonic modules interacting with each other. Each module is surrounded by a listening perimeter that defines the maximum distance required for two modules to affect each other. When multiple modules are within hearing distance, each module will react to the closest one. This is represented on the diagram by the direction of the arrows. Modules can either be mutually affected or in a chain reaction, which creates harmonic clusters as can be seen on the image. Each cluster of connected modules is a consonant chord, because each interval from the chord is either a perfect fourth, fifth, or unison.

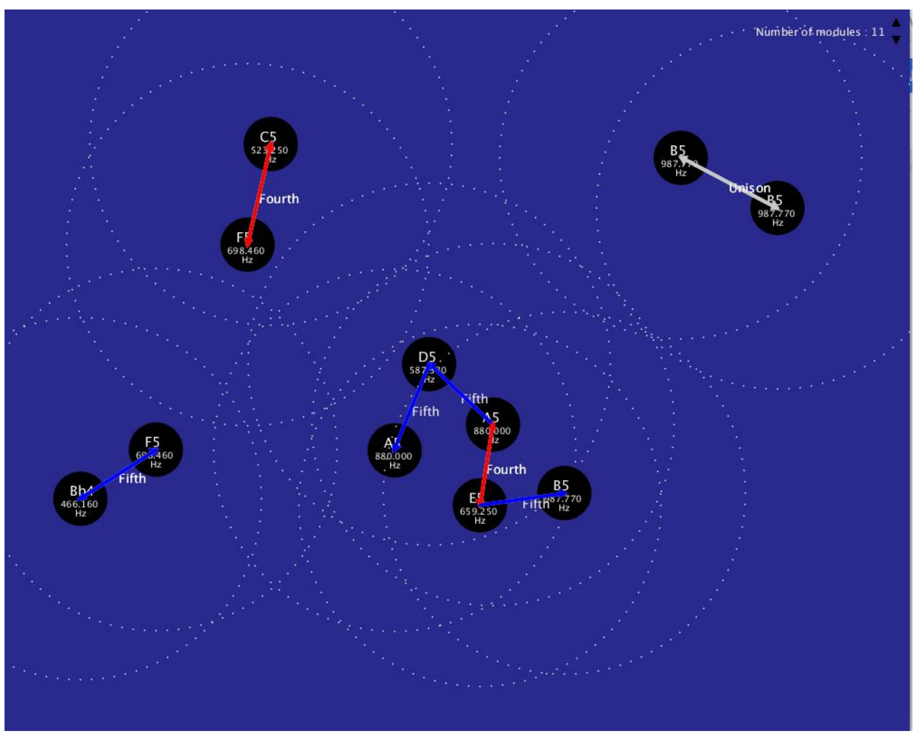


Figure 19: Digital simulation of *Harmonic Sound Insect*

The following images show the simulation of different sound chords generated by various spatial setups of the modules. Figure 20 is an example of a layout where all the modules are too distant to hear each other: the sound that arises from this setup is very dissonant (as can be heard here). Figure 21 shows a different layout where a cluster has been created but some modules are still not connected to others. In the recording, we can hear (link) that the level of disorder has decreased but that the sound created still presents some dissonances. Figure 22 is an example of a completely synchronised layout, where all the modules are close enough to affect each other, creating a consonant chord (as can be heard here).

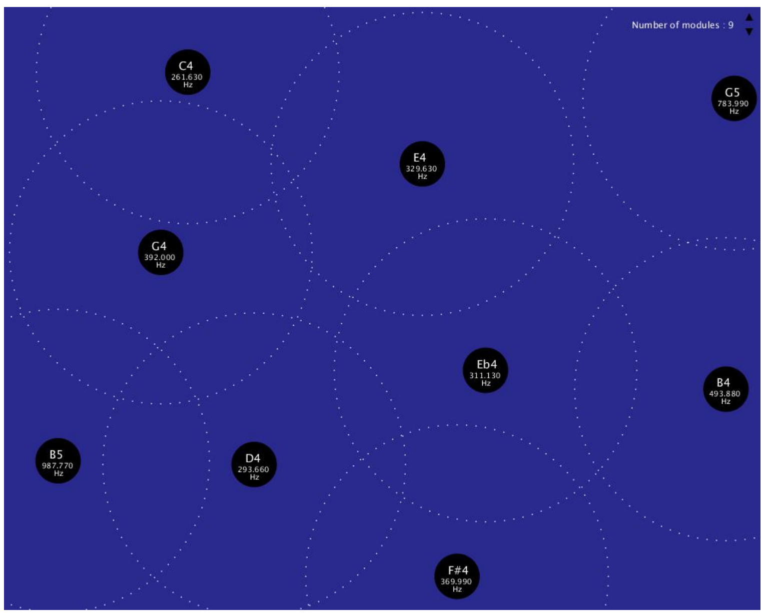


Figure 20: Non-organised system of *Harmonic Sound Insect*

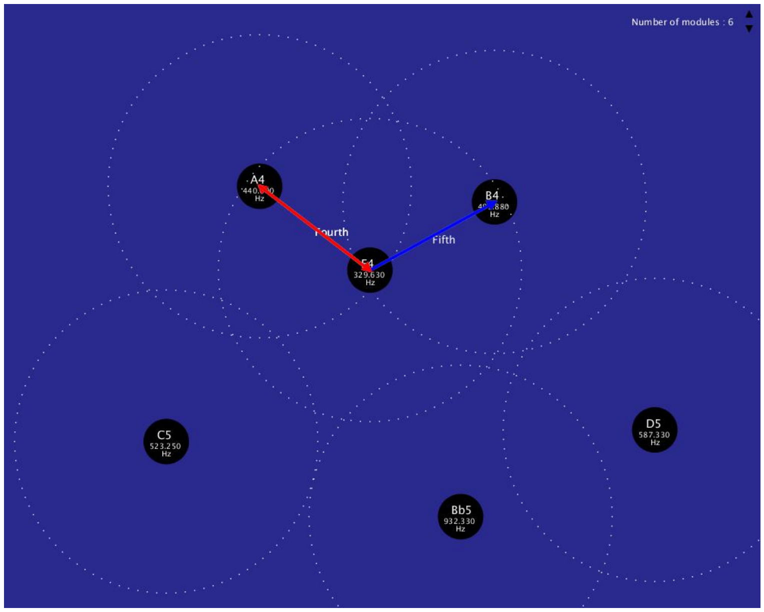


Figure 21: Partially organised system of *Harmonic Sound Insect*

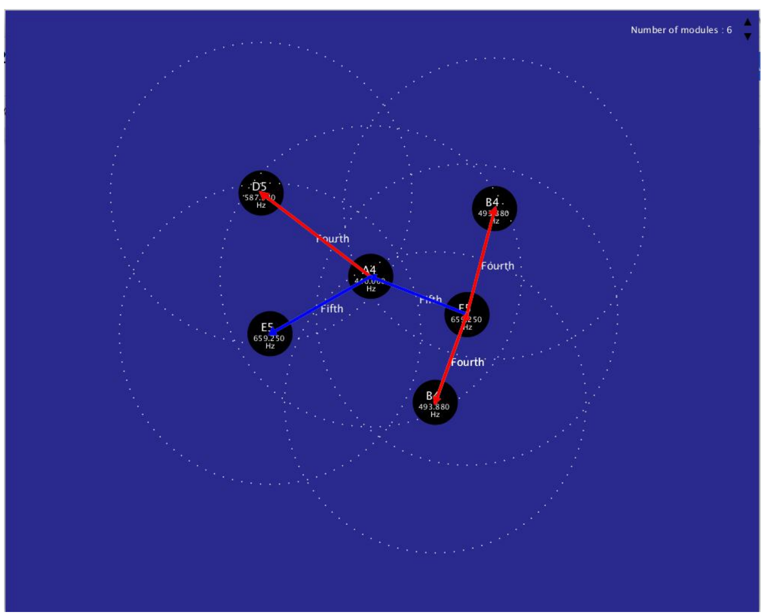


Figure 22: Completely organised system of*Harmonic Sound Insect*

## 5.2 Condition 2 : An analog communication media as source of disorder

In *Sound Insects*, the environment of each module is defined by acoustic limits, from the surface of the module to the surfaces of the room it is in. Because the modules' unique sense is hearing, any part of their environment that either generates sound (modules or audience interacting with the modules) or modifies sound (the walls of the room reverberating sound, audience blocking the path of sound between modules) will be interpreted by the module as a signal (Figure 23).

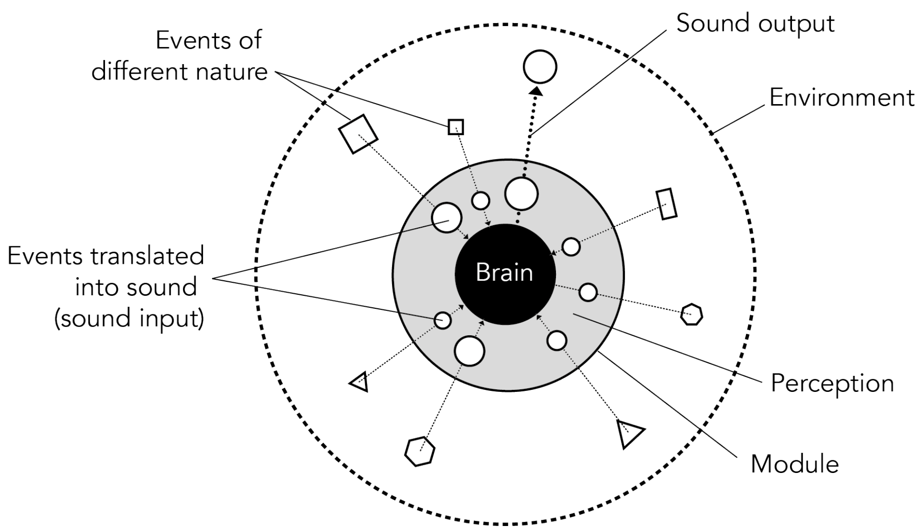


Figure 23: Composition of a module

Communication through analog media therefore inevitably leads to interpretation, that can be defined as the reception of a translated message. Interpretation creates disorder as it transforms the information present in the signal, and increases the chances of "misinterpretation" leading to a disruption in the stability of the system. The figures presented hereafter show how analog communication with sound (Figure 25) in opposition to digital communication (Figure 24) can engender misinterpretation leading to disruption in the system.

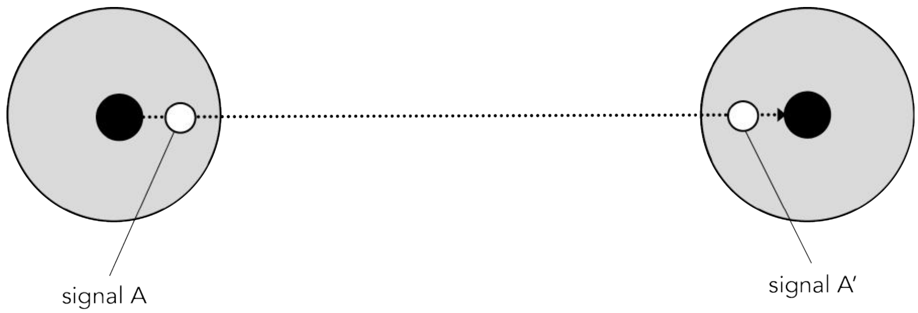


Figure 24: Digital communication between two modules

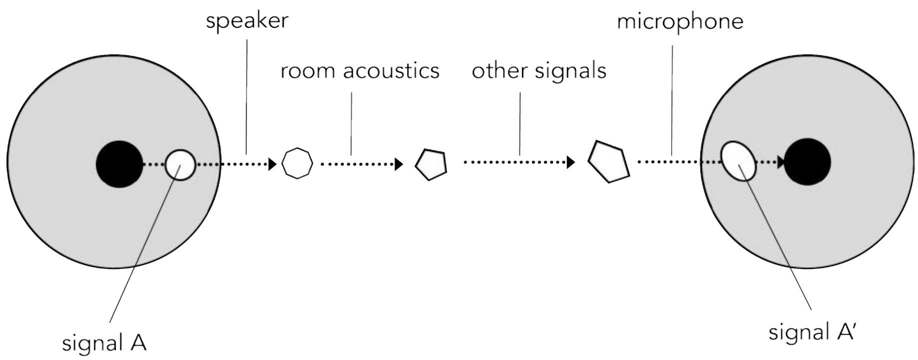


Figure 25: Analog communication between two modules

*Rhythmic Sound Insects* (Prototype 1) are very susceptible to their environment as any event, such as people walking in the room, closing the door or simply talking next to a module, will trigger a sound signal. The intensity of those sounds are often a lot higher than the modules' own sound output, and can therefore hardly be filtered out of the modules' perception. In this situation, the level of disorder coming from the environment can sometimes be too high to enable the emergence of order. Indeed, the set of initial conditions is being reset too often without letting enough time to the system to self-organise and stabilise the emergent patterns. From a listener's perspective, the performance arising from the system in such scenarios is perceived as random or completely chaotic. It is only in rare occasions that the environment is quiet enough for the audience to assist to the emergence of rhythm.

In *Harmonic Sound Insects* (Prototype 2), the use of a specific range of frequencies should reduce the level of disruption coming from the environment. For this new prototype a range of notes have been chosen and these correspond to the frequency of the human voice (from C4: 261 Hz to C6: 1046 Hz) to avoid lower or higher frequencies to disturb the system, while enabling the audience to interact with it.

The main source of disruption in the environment comes from the audience observing and interacting with the system. In both prototypes, people coming into the room are invited to reset the initial conditions of the system by either moving the modules to different locations or by producing sound.

## 5.3 Condition 3 : An entity responsible for the reinforcement of musical emergence

The modification of the system decided by the audience members acts as a reinforcement of the emergent (positive feedback) as a way to create order, or as a disruption of the emergent (negative feedback) as a way to create novelty.

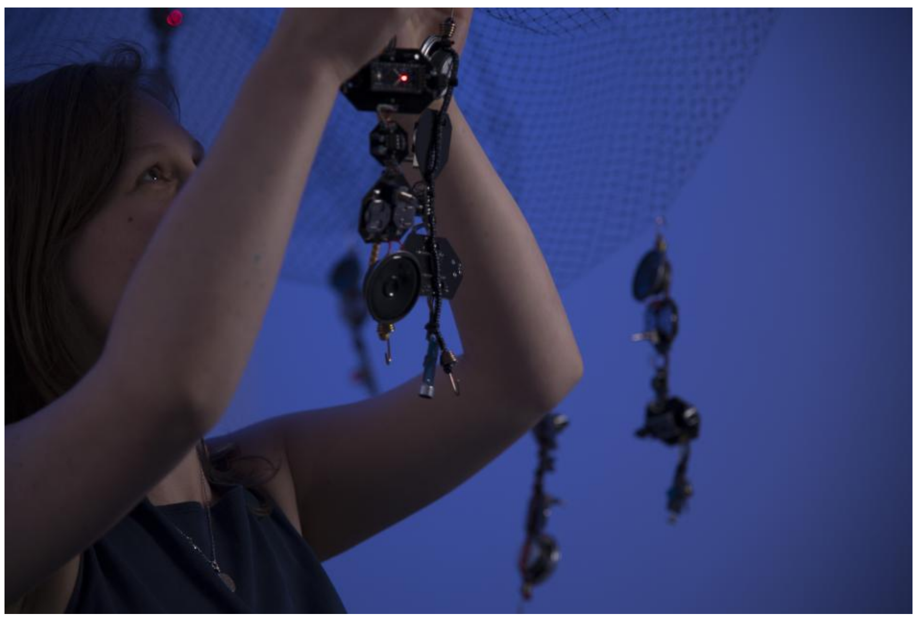

Figure 26: Audience interacting with the modules, *Rhythmic Sound Insects* (2018)

It might seem that the audience entirely controls the performance of the system, which would go against the aim to produce musical unexpectedness. However, in reality, even though members of the audience can understand the behaviour of individual module and act upon it, it is extremely difficult to predict the response of the whole system, especially if the audience is playing with *Sound Insects* for the first time. Being in this unstable situation, between control and surprise, between order and disorder, between patterns and randomness, is exactly the state in which musical improvisational systems evolve.

# 6 Conclusion and future research

This thesis has discussed multiple analogies between different types of self-organising systems in nature (swarms), society (improvisation in theatre and music) and computer science (cellular automata). For each, their ability to organise following a set of rules, to generate or respond to disruption and to evolve to create an aesthetic outcome has been analysed. The sufficient conditions for musical emergence that have been stated in this thesis coincide with the results of most research on the same topic: interaction rules, disorder, positive and negative feedback. These conditions have been widely used in academic research, in the fields of musical composition and computer science, and have lead to the development of several generative music algorithms. It is quite surprising to notice the contrast between the profusion of academic work or computer-based artwork and the lack of physical artwork based on the phenomenon of musical emergence. This is why *Sound Insects* has been created: inspired by the observation of self-organising systems, this installation aims at creating a new musical performative object. It sits at the intersection between instrument and performer, inviting the audience to engage with the process of improvisation.

Designing and building an entire physical self-organising sound system brings up a lot of challenges that digital simulations usually avoid, such as dealing with restrained processing capabilities, voltage drops due to the use of independent batteries, broken modules, faulty connections etc. *Sound Insects* needs further development in order to overcome those issues and create the desired effect, but has offered promising results so far in terms of audience participation and in the emergence of rhythm and harmony. The research carried out for this thesis and the concurrent design process are positive first steps towards the birth of a creative tool that could bring musical performance and composition towards unexplored paths.

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