COMPOSING INTERACTIONS

Dissertation by

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Submitted for the Degree of
Doktor der Philosophie

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November 2017

Abstract

This thesis investigates interaction in the context of computer music composition in general and performance-oriented generative music practice in particular. The research follows three approaches of inquiry.

The first one consists in a scholarly and theoretical analysis of the concept of interaction and its understanding in the field of computer music. Furthermore, the topic is put in relation with theories of *perception* and *cognition* in philosophy and cognitive sciences, in particular with the concepts of *embodiment* and *enaction*. An understanding of interaction as a temporal process of *mutual influence* taking place between agents is introduced. At this point, the concept *agent* evolves into a central topic of this dissertation.

The second direction of research is based on the mathematical theory of *dynamical systems*. The framework affords a *process-based* mindset and an *ecological* perspective that emphasises the role of interrelations between elements in a system. In the context of this work it is understood as the most apt language for formulating and understanding processes of interaction.

A third approach consists in personal *artistic engagement* in the development of interactive computer music environments. This thread interweaves with the former two and allows for continuous *aesthetic experimentation*: speculations and abstract intuitions are put into perceptible form and, in turn, concepts and formulation can be sharpened by experience. An essential part of this engagement relies on the software framework *rattle*, which has been developed for the formulation and the real-time simulation of dynamical systems.

The dissertation develops an attitude towards interaction that employs the language of dynamical systems to address the agency of generative computer music processes. Eventually, *agency* is re-interpreted as an essential perceptual quality generative computer music systems should be afforded with to allow for a composition of interactions to emerge.

Zusammenfassung

Diese Dissertation untersucht Interaktion im Kontext der Komposition von Computermusik im Allgemeinen sowie der Praxis performance-orientierter generativer Musik im Besonderen. Die Forschung verfolgt drei methodische Ansätze:

Der erste Ansatz besteht in einer wissenschaftlichen und theoretischen Analyse des Konzeptes von Interaktion und dessen Verständnis im Bereich der Computermusik. Dieses Thema wird in Relation mit Theorien von *Wahrnehmung* und *Kognition* innerhalb von Philosophie und Kognitionswissenschaften gestellt, insbesondere durch die Konzepte von *Embodiment* und *Enaction*. Eingeführt wird eine Auffassung von Interaktion als einem zeitlichen Prozess *gegenseitiger Beeinflussung*, die zwischen Agenten stattfindet. An dieser Stelle entwickelt sich das Konzept des *Agent* zu einem zentralen Thema der Dissertation.

Die zweite eingeschlagene Richtung der Forschung basiert auf der mathematischen Theorie *dynamischer Systeme*. Dieses Bezugssystem gewährt eine *prozessbasierte* Denkart und eine *ökologische* Perspektive, welche die Rolle von Wechselbeziehungen zwischen Elementen eines Systems betont. Im Rahmen der vorliegenden Arbeit wird dieser Ansatz als die geeignetste Sprache betrachtet, um Prozesse der Interaktion zu formulieren und zu verstehen.

Ein dritter Ansatz besteht in der persönlichen *künstlerischen Beschäftigung* mit der Entwicklung interaktiver Computermusikumgebungen. Dieser Strang wird mit den beiden vorherigen verwoben und ermöglicht das kontinuierliche *ästhetische Experimentieren*: Vermutungen und abstrakte Intuitionen werden in wahrnehmbare Form überführt, und umgekehrt können Konzepte und Formulierungen durch die Erfahrung geschärft werden. Ein wesentlicher Teil dieser Beschäftigung stützt sich auf das Software-Framework *rattle*, das für die Beschreibung und Echtzeitsimulation dynamischer Systeme entwickelt wurde.

Diese Dissertation entwickelt einen Standpunkt hinsichtlich Interaktion, welcher die Sprache dynamischer Systeme gebraucht um, die Wirkmächtigkeit generativer Computermusikprozesse zu erfassen. Schlussendlich wird *Wirkmächtigkeit* (*agency*) als eine essentielle Wahrnehmungsqualität neu interpretiert, mit welchen generative Computermusiksysteme auszustatten sind, um das Komponieren von Interaktionen zu ermöglichen.

Acknowledgments

To my partner Theresia for her encouragement and support.
To Martin Rumori and Hanns Holger Rutz for their friendship and the inspiring discussions.
To my mother Ella and my father Giuseppe for their assistance and their motivation.
To all my friends and colleagues.
To the Institute of Electronic Music and Acoustics in Graz for being a great place to work.
To Agostino Di Scipio for being a great source of inspiration.

To my supervisors Prof. Gerhard Eckel and Prof. Robert Höldrich for their guidance and the exchange of thoughts, ideas and experiences.

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1 Introduction

Introductions are written last and this one is not an exception. The chapter is the last written after a work that traversed years of engagement with different research themes, projects, but also artistic practices. It feels more like a conclusion than a preface. Of course, it should accomplish the task to frame what will come next, easing the entrance into the following text. But, it should also transcend this aim in that, knowing where I will be headed at, already provides some building blocks that attempt to actively shape the understanding of the reader, without giving too much away.

To this end, this chapter first presents a personal introduction to this work, the motivation behind it. Then, a "historical" reconstruction of the path that led to this work will follow, next to a clarification of the methods which have been used.

1.1 Motivation

This dissertation has its origin in a practice of *Computer Music*: one could say it is "practice-motivated".

Coming from a more traditional, acoustic, mode of musical performance, encountering computer music I was fascinated by the world of possibilities it offered. I could enter the smallest details of synthesis and simultaneously work on the organisation of sound in time. All temporal scales of a musical composition seemed to be accessible at once. The most interesting aspect were the most diverse modes of *physical* engagement with sound that the computer made possible: a previously unimaginable promise and an Utopia of a bodily engagement with composition and sound.

But, to this fascination corresponded a fundamental frustration with the actual state of performative practice in computer music. Somehow there is a felt incoherence or *dissonance* in those practices, including e.g. Live-Electronics, between the space of possibilities offered and the modes through which these can be engaged with. As the role of the performer reduces to that of a mere "controller" of an often very complex computational machinery, the promise could not be maintained. I know now, that part of the problem lies in a prejudice of how and what musical engagement means, a mindset that does not do justice to the specificity of the computational medium.

At the time of the beginning of this thesis' research path, my interpretation of the problem was that of a lack of *interactivity* from the part of the computer, and this was the problem I set to tackle. This theme is of course not unknown in computer music research and has been addressed in many different ways and from many perspectives.[1] The source of trouble is typically located at the split between the sound synthesis processes and the interface they present for the user's or musician's interaction. And so, the aim of this research was to understand how interfaces could be designed that could allow for a more engaging, physical, bodily and intuitive relationship with the computer music systems.

[1] Newton Armstrong. *An enactive approach to digital musical instrument design*. PhD thesis, Princeton University, 2006; Bob Ostertag. Human bodies, computer music. *Leonardo Music Journal*, 21:19-23, 2006; and F Richard Moore. The dysfunctions of midi. *Computer music journal*, 12(1): 19-28, 1988

Even if through the years questions have changed their form, *interaction in computer music* is, still, the core theme of this dissertation: the development of an attitude towards the interaction in computer music which addresses fundamental qualities of interaction and of computer music.

1.2 Historical Path

The research question the dissertation was set to answer at its beginning, could be formulated as:

> *How can more bodily and intuitive interaction methods for computer music instruments be designed on the basis of simulated physical models?*

Two main factors were the reason for this particular formulation. The first being that I previously had studied Theoretical Physics with a particular emphasis on Computational Physics. I had therefore already some theoretical and technical knowledge that would allow me to address the problem. But, the most important factor was that I was involved in the *Embodied Generative Music* research project at the *Institute of Electronic Music and Acoustics* in Graz. The project's main research theme was the dissociation of sound and bodily movement pursued from both a scientific perspective as well as from a performance-oriented computer music practice. Due to its thematic proximity, the project was extremely influential to this work.

The idea behind the question above was to develop a practice in the design of interfaces for the interaction with sound synthesis and computational processes which tapped into our implicit bodily knowledge of the physical world. Our knowledge of the "mechanisms", the rules the physical world exposes to us when we interact with it through our bodies. By developing interfaces based on the modelling and the simulation of such processes, the idea was to elicit resonances in the user or the performer on a bodily level as such processes would resemble dynamics we would know from the interaction with our environment.

A theoretical basis for this perspective as well as for the Embodied Generative Music project was the *Embodiment Theory* of cognition. The theory holds that the human perceptual system as well as motor systems are responsible for shaping fundamental aspects of human cognition. As the body and its interactions within the environment is essential in the formation of higher functions of our brain, cognition is not anymore a function that is detached from the world and from the body in which it is placed. The theory affirms that thought processes happen in a physical medium, which transcends its function as physiological substrate and becomes active in the very shaping of thought itself. The embodiment theory arises in the context of philosophy, but its effects spread over to various research fields including neurosciences, psychology, linguistics, neurobiology, but also robotics and artificial intelligence. It offers a new perspective to disciplines seeking ways to include the body in their thinking. Therefore, embodiment theory finds its way into the fields of interaction design and in particular computer music, where it is the basis for addressing concerns regarding the lack of bodily presence in composition and performance.

Our understanding of embodiment was that of an extension of the body into the unfolding, generative sound process. Dancers would be able to extend their proprioception such that their body would be allowed to *inhabit* the sound. The metaphor we used to describe this situation was that of the slipping into a dress, which then would follow the movements continuously adapting itself according to each action. We were therefore following what could be considered a classical *Human Computer Interaction* approach in searching for design strategies which would generate *transparent interfaces*. An interface which does not posses a recognisable character a materiality itself, but is an ideally non-conditioning information passing channel between the performer, who is providing the input, and the actual system, which is to be fully controlled. The interface just accomplishes a task which is purely functional in linking these two actors, to connect the user with what is "behind" the computer music system.

This thoughts were inevitably interwoven with the artistic works I was engaging with both within the *Embodied Generative Music* project and in my own practice. This practical, artistic and aesthetic engagement was instrumental in showing that this perspective, our understanding of embodiment and of the tools we were using for realising interactive environments, were not sufficient to address the relation between performer and computer music system we were seeking. In particular, the aspect of interaction with real-time generative computer music processes, seemed to be a qualitatively different problem that needed other conceptual tools.

This was the moment in which a search for an alternative understanding and theoretical framing begins; an inquiry that forces to re-think and the premises of this research and to question the concepts on which it based.

- What are computer music instruments?
- How can interaction be defined?
- What are physical models?
- How do they resonate with perception?
- How does perception work?
- What does "bodily" mean?
- ...

These are just some of those questions. They have a very general character and in fact, at this point this work experienced a dramatic broadening into the most diverse directions. Looking for directions I ventured into neurophysiology, cognitive sciences, philosophy, interaction design, dynamical systems theory, cybernetics to name a few. That is, into a nexus of different research streams, which would blow the theme of this dissertation into vast dimensions: with respect to Umberto Eco's recommendations for narrowing down a thesis' subject subject[2], the exact opposite direction. Nevertheless, a very inspiring one. This moment of broadening though, resulted in a sort of dispersion of the central question, a *pulviscular* state of the research in which many ideas, concepts and experiences were "floating around" with unclear connections.

[2] Umberto Eco. *How to write a thesis*. MIT Press, Cambridge, Massachusetts, 2015

The word *pulviscular* is not really an English word. It has been used in order to translate the idea of the Italian "pulviscolare" which has been used by writer Italo Calvino in some of his texts. Apart from my personal liking, the meaning of the word as indicating something that is constituted by fine dust (not dusty) or by a multitude of almost impalpable particles, fits the image

I'm trying to convey. Considering the use the author makes of this word, it seems even more apt as it describes the idea of a text which, rather then presenting linear narrative development, is *constructed* by the reader: he or she identifies particles or concentrations of interest, draws connections between them generating a vibrating net through which the substance reveals.[3]

[3] Italo Calvino. *If on a Winter's Night a Traveler*. Houghton Mifflin Harcourt, 1981

> *Reading is a discontinuous and fragmentary operation. Or, rather, the object of reading is a punctiform and pulviscular material. In the spreading expanse of the writing, the reader's attention isolates some minimal segments, juxtapositions of words, metaphors, syntactic nexuses, logical passages, lexical peculiarities that prove to possess an extremely concentrated density of meaning. They are like elemental particles making up the work's nucleus, around which all the rest revolves. Or else like the void at the bottom of a vortex which sucks in and swallows currents. It is through these apertures that, in barely perceptible flashes, the truth the book may bear is revealed, its ultimate substance.*

I regard this thesis is the textual trace of a movement of reconstruction, a condensation of this "dust" into a few gravitational centres. In some parts its original pulviscular nature might still be sensed; the hinted narrative path I have attempted to contruct should help the reader.

1.3 Research Methods

The dissertation relies on an ensemble of research methods.

I have used *scientific methods* in the analysis of the existing research literature in computer music research and further in addressing specific directions in cognitive sciences and philosophy. These investigations served as basis for the formulation of ideas and hypotheses.

Further, I have employed *technological research* methods while developing software tools in order to test my assumptions. Not only the realisation of these instruments in part involves multiple cycles of hypothesis building, experimentation, testing and step-wise improvement towards an aim. Moreover, in my experience, this processes cannot be reduced to purely functional activities i.e. only defined by the final output they produce. Especially in this case, the process of development reflects back on the overall research process also on a more conceptual level: the formulations in form of functioning code of abstract ideas affect how those ideas will be experienced and re-formulated. I therefore regard the direct engagement in the development of the software tools for my research not only a necessity, but also as a valuable method of research.

The most important method in this dissertation is however *artistic practice*. The praxis of computer music itself became one of the most important tools in order to address issues of interactivity. Not only in a sense of a production of pieces or even of "proof of concepts", rather in a purely experimental sense. Artistic practice has been used as a tool for generating the conditions in which specific attributes of *interaction* might be seen: an experimental condition "whose outcome cannot be foreseen".[4]

[4] Bob Gilmore. Five maps of the experimental world. *Artistic Experimentation in Music: An Anthology*, pages 23-29, 2014

The artistic works I report here, do not have a function of a "result" or of an arriving point, they are instead charged with a "generative" character, of experiences and of reflections. They are artefacts through which speculations could be pursued, inspiration can be drawn from for new questions or for reaching clearer formulations. I see these artefacts form a dialectical relationship with the concepts and the technology I used in this dissertation. Further, considering that the issues about *interaction* are primarily *aesthetic*, artistic works might by the primary access method to those questions.

At this point, as throughout this text I make use of the term *aesthetics* in diverse forms (e.g. as *aesthetic experience*), it seems necessary to elucidate the term. This is not a dissertation in philosophy and I am not trained in this discipline: so I will not be able to cover all aspects of this concept which has been and still is the subject of numerous controversies since the last 300 years of philosophical discourse. Therefore, I will limit myself to clarifying with which connotation and intention it is used in this text and will not try to be exhaustive.

I understand the aesthetic in the sense of the German "Rezeptionsästhetik" i.e. the philosophical discipline which considers the sensuous and cognitive reception of artistic works and in particular how this reception is influenced by factors that may be located in the work itself. A good example of what I mean is how Umberto Eco understands an "Open Work": a work, in his case a text, which allows for multiple interpretations and meaning, whose primary value is to permit and elicit the readers' (or the audience's of a piece of Brecht in Eco's examples) interpretative action. It is a work that does not present a "solution", but the affordances to construct one. It is therefore in the artistic work that qualities are placed which affect and evoke mechanisms of perception and cognition.[5]

[5] Umberto Eco. *Opera aperta*. Harvard University Press, 1989

The aesthetic I am interested in does not refer to questions of the formation of taste, or to the qualities that make an object be judged as work of art, but to questions of perception, more precisely to the *shape of perception*. An aesthetic object is in this sense not just a perceptual object, but an artefact whose nature is to bring the mechanisms of perception to light; an aesthetic experience is an experience that points to the function of perception, it makes it conscious. Philosopher Alva Noë holds that in an inquiry in perceptual consciousness, and therefore in aesthetics in this sense, artistic practice could be the most effective tool.[6] Noë refers here to the understanding of artistic practice of installation artist Robert Irwin as he writes:

> *To be an artist is not a matter of making paintings or objects at all. What we are really dealing with is our state of consciousness and the shape of our perception.*[7]
>
> *The act of art has turned to a direct examination of our perceptual processes.*[8]

I fully share this understanding of artistic practice. Therefore, as the phenomena this work focuses on are of a perceptual nature, following this reasoning, artistic praxis seems the best method to address them.

Thus, the role of the artistic works I collect in this work, especially in the appendix, is a structural one: they are arguments which are instrumental in the research and cannot be relegated outside this dissertation. These works cannot be separated from the reasoning and development process in which they appeared and that process was strongly influenced by them in turn.

[6] Alva Noë. Experience and experiment in art. *Journal of Consciousness Studies*, 7(8-9): 123-136, 2000

[7] Robert Irwin. The state of the real. In Beatrice Hohenegger, editor, *Notes Towards a Conditional Art*, chapter 7, pages 49 - 53. Getty Publications, 1972a

[8] Robert Irwin. Re-shaping the shape iof things. In Beatrice Hohenegger, editor, *Notes Towards a Conditional Art*, chapter 8, pages 54 - 60. Getty Publications, 1972b

1.4 Structure of the Thesis

The "condensation" operation I've described above, produced three major axes, along which this dissertation unfolds: each is treated in one of the central chapters of the text. Each chapter follows its own narrative, which is why the transitions may appear a bit abrupt: the themes they centre on are of very different nature. There is a red thread joining them, which will emerge through the process of reading.

The work is organised as follows:

- Chapter 2 Interaction departs from the historical development of electronic, computer music. The theme of interaction is introduced as it appears in these practices and is then brought in context with the themes of the embodied cognition theory and then later with the enactive approach, which is a core element of this work. In this chapter definitions of most of the terms used in the text are given.

- Chapter 3 Dynamical Systems introduces the theory of dynamical systems. First from a mathematical perspective, but then in an understanding of a general language and thought framework for processes of temporal evolution and interaction. An explanation follows showing how this language is used in cognitive sciences, the study of perception and in computer music and provides a justification for its use.

- Chapter 4 Case Studies describes a path through the actual technical and artistic engagement with the theme of interaction. The three case studies discussed in the chapter are the most important ones in terms of the effects they had. It starts from the development of a software framework, passes through artistic research in the context of the *Embodied Generative Music* project, and ends with in a study employing a dynamical systems perspective in the development of a computer music environment for interaction.

- The Chapter 5 Conclusions and Outlook offers a résumé of the thesis and highlights its central claims. Furthermore, prospective and ongoing research directions connected to this work are described.

- The Appendixes contain diverse materials. First, A catalogue of works in appendix A, collects descriptions of some of the artistic works which were central for this dissertation. The remaining sections are concerned with detailed descriptions of the formulations used in the implementations of the tools used.

2
Interaction

This chapter tries to collect the most important concepts I operate with later in this work. It further provides the context to which these concepts are tied with: at least the context from which I have drawn them, there is therefore no claim for completeness. In doing so, a narrative is constructed which starts from the historical beginnings of electronic and computer music goes through the appearance of live-electronics and interactive practices, touching on ecological psychology and embodiment cognitive theory and ends with the theory of enaction and agency. *Generative music*, *live-electronics*, *interactive composing*, *affordance*, *ecology*, *embodiment*, *enaction* and *agency* are some of those concept which will appear on this path.

2.1 Computer music: a generative art

The central theme of this work, as its title hints, relates to the theme of *interaction* specifically in the context of computer music composition.

Interaction seems to have become an ubiquitous term nowadays. Generally speaking it indicates the ability of a tool, mostly a digital tool i.e. a programme that is executed on some digital device or computer, but also simpler artefacts like sliding doors, to be able to accept or sense input and adjust its state according to some internal rules. This characterisation attempted here is of course very broad and very unclear when it is confronted with specific situations.

In the field of *Electronic Music*, questions of interactivity played a role, either implicitly or explicitly, since its beginnings. The fundamental cause of the raised importance of this issue being that early electronic music researchers operated with instruments which presented a relationship between the bodily action of their operators and the sound generation which was radically different than the acoustic instruments mostly used before. Those instrument have a much smaller, if at all, dependence on the energy input through gestures or in general, bodily movement by their players. One could say that in general the ratio between energy which is "injected" in the instrument's system by the operators body movement and its perceived effect, is some orders of magnitude smaller in the case of a *Moog* synthesizer, than for a doublebass.

That does not necessarily mean that those new instruments have become suddenly so much more efficient: instead, the cause for this dramatic change, lies in the injection of a second form of energy (beside that provided by the human body) into the instruments' system, *electrical* energy. In a way, this form of energy provided means of an *amplification* or even an indefinite *sustain* of an operator's actions, reducing the effort in terms of bodily energy needed for sound generation or almost eliminating it: it is a (felt) *infinite* source of power and therefore, possibilities. That is, the use of a secondary energy source, the electrical power, in conjunction with the means of manipulating it, at the same time provided means for exploring a vast new space different of sound generation mechanisms as well as substituting human bodily energy in direct intervention less and less necessary.

A big exception to the previous considerations might be found in the organ. This instrument which precedes any electronic instrument, implemented a similar in fact using an additional source of energy in order to greatly amplify the player's actions. It is not surprising that many of the first elecotronic instruments, like the *Dynamophone* or Oskar Sala's *Trautonium*[1], but also most of the later synthesizers like the *Moog*[2] relied on the metaphor of the organ in designing their instruments.

The loosening of the tight connection between body and sound generation opened a gap between the two where there was a continuity before. This aperture offered space for a re-composition of this relationship, a space of possibilities to re-think the body-sound relationship: the most clear examples being the *theremin*[3] or the *terpsitone*.

With the advent of early digital computing machines, *Computer Music* developed out of the *Electronic Music*[4] inheriting the above qualities of the relationship between bodily action and sound producing devices, but also bringing into play new and distinctive qualities to compositional practice. The Computer, the medium in which this kind of music is composed, allowed for a fundamental shift in music making: this "instrument" in fact greatly facilitates the formulation and the execution of *processes*, programmes or algorithms able to generate complex formal structures. *Algorithmic composition*, the praxis in which musical scores are generated departing from a set of rules devised

[1] André Ruschkowski. *Elektronische Klänge und musikalische Entdeckungen*. Reclam, 1998

[2] Robert A Moog. Voltage-controlled electronic music modules. In *Audio Engineering Society Convention 16*. Audio Engineering Society, 1964

[3] Leon S Theremin and Oleg Petrishev. The design of a musical instrument based on cathode relays. *Leonardo Music Journal*, 6(1):49-50, 1996

[4] A clear distinction between *Electronic Music* and *Computer Music* might seem, at least these nowadays, difficult as almost every electronic device is in fact integrated with computer. The distinction I try to hold here is used as a rethorical tool to make specific characteristics of different practices as they emerged historically clearer.

by the composer, and which has been applied in compositional praxis to various degrees since Guido d'Arezzo[5] (early middle Ages), experienced a great upswing. Lejaren Hiller is recognised as one of the very first experimental computer music composers to engage at that time with the novel possibilities with the *Illiac* computer installed at the University of Illinois, Urbana-Champaign.[6]

With the subsequent widespread diffusion of the tape recording technology and sound projection devices, joint with the capabilities of sound synthesis computers had achieved, a further fundamental development was accomplished. At this point not only computer music offered and unprecedented range possibilities of the *simultaneous* composition of sound and music. More importantly, this wide space of possibilities could be accessed in total independence from further human interpretation: as loudspeakers could be used for sound projection, the complete process of composition, realisation and performance was in the composers' hands. There was no need anymore to rely on performers to have one's music generated and no need to cope with the indeterminacy and the subjectivity of human interpretation: the composers' desire for total control was near to its realisation. The establishment of electronic music studios consolidated an emergent compositional practice where the composer would work in isolation and autonomy.

Early composers who pursued this directions not only realised groundbreaking musical works, but also generated and contributed to new discourse in and around composition exposing their practice and their thoughts in textual form. Herbert Brün[7], Gottfried Michael Koenig[8] and, most notably, Iannis Xenakis[9], just to name a few who where decisive for the future developments in the computer music.

Considering the general context, this musical practice shared some of its roots with the general movement of *conceptual art* which strongly influenced artistic practice especially in the visual domain. As summarised by Sol Lewitt[10]:

> *In conceptual art the idea or concept is the most important aspect of the work. When an artist uses a conceptual form of art, it means that all of the planning and decisions are made beforehand and the execution is a perfunctory affair. The idea becomes a machine that makes the art.*

Algorithmic art and computer art movements developed these ideas even further towards an abstraction from matriality as for example in the work and the writing of Georg Nees and Frieder Nake: "Computer art is concept

[5] Gerhard Nierhaus. *Algorithmic composition: paradigms of automated music generation.* Springer Science & Business Media, 2009

[6] Lejaren Arthur Hiller and Leonard M Isaacson. *Experimental Music; Composition with an electronic computer.* Greenwood Publishing Group Inc., 1979

[7] Herbert Brün. *über Musik und zum Computer.* G. Braun, 1971

[8] Gottfried Michael Koenig. Kompositionsprozesse. In *Ästhetische Praxis*, volume 3 of *Texte zur Musik*, pages 191-210. PFAU Verlag, Saarbrücken, 1993

[9] Iannis Xenakis. *Formalized music: thought and mathematics in composition.* Pendragon Press, 1992

[10] Sol LeWitt. Paragraphs on conceptual art. *Artforum*, 5(10): 79-83, 1967

art insofar as it describes an idea and does not show the material work"; "Computer art shares with conceptual art [...] a neglect of materiality".[11] With a similar gesture, computer music at this time sought an (almost) complete disconnect from traditional modes of musical performance. Processes of production, rules and algorithms the computer was programmed to follow were the central protagonists.

[11] Frieder Nake. Paragraphs on computer art, past and present. In *Proceedings of CAT 2010 London Conference*, pages 55-63, 2010

These movements resulted in what today is known as *Generative Music*. Pushed by the advent of personal computing during the '80 and by the development of high level programming frameworks for sound synthesis and algorithmic control (e.g. Max was developed by Miller Puckette at IRCAM and made public around the beginning of 1990) generative music started to play a growing role in music production and still is, as the recent works by composer Brian Eno testify. A kind of music in which the composer/musician would create the process which generates the music, a process that would then develop without necessary human intervention. Specifically in the case of *generative computer music* that would then translate to "produced by leaving a computer program to run by itself, with minimal or zero interference from a human being" as Nick Collins says.[12] Generative computer programs could then be considered as examples of *derivative intentionality*[13] where the code, the algorithmic formulation is written by the human composer who then retreats and yields the autonomy of the actual execution to the machine.

[12] Nick Collins. The analysis of generative music programs. *Organised Sound*, 13(3):237-248, 2008

[13] John R Searle. *Mind: a brief introduction*. Oxford University Press, 2004

Generative music is a praxis that resonates with the intrinsic characteristics of the computational medium: it provides the tools for the formulation of processes and at the same time the space for their realisations, their actualisation. Throughout this work, whenever I will refer to computer music, I will understand this particular facet.

2.2 Live-Electronics and interactive composing

A sort of *process composing* or *composition of processes* is of course not appearing as a central theme only in the context of computer generated music. In particular John Cage's work was paradigmatic in this sense and transcended the boundaries drawn by the specific means employed in its realisation. "I was to move from structure to process, from music as an object having parts, to music without beginning, middle, or end, music as weather."[14], he said about his compositions. Many of his works (as for example *Fontana Mix*) would consist of instructions for how the score of the piece to be performed could be generated: that is, he provided performers with the directions needed

[14] John Cage. John cage: An autobiographical statement, 1990. URL http://johncage.org/autobiographical_statement.html. Accessed on 29/10/2017

for initiating a process of putting together, literally composing, in a certain fashion the materials of the piece. Most of those processes included and depended on aleatory elements, operations of chance whose function was to steer the construction of the work away from the idiosyncrasies of personal taste or subjective interpretation. Cage used those operations with the aim to free the composition and himself, the composer, from individual taste and memory and to initiate a process which would produce something he did or could not think of, to be, in a way, surprised. In his words:[15]

> *What actually happened was that when things happened that were not in line with my views as to what would be pleasing, I discovered that they altered my awareness. That is to say, I saw that things which I didn't think would be pleasing were in fact pleasing, and so my views gradually changed from particular ideas as to what would be pleasing, toward no ideas as to what would be pleasing.*

[15] John Cage and Roger Reynolds. An interview with john cage on the occasion of the publication of silence. *Generation - The University Inter-Arts Magazine*, pages 40-51, November 1961

Of course, the use of chance was, for similar reasons of the above, one of the fundamental ingredients also for the computer aided algorithmic composition. Cage was not only aware, he was involved: together with Lejaren Hiller he composed the piece *HPSCHD* at Experimental Music Studios at the University of Illinois at Urbana-Champaign, a composition based on a random sampling of scores and pre-recorded tapes controlled by computer processes.

But there was more to his use of chance or *indeterminacy*. It was his way to embrace the indeterminacy of the world and of performance, juxtaposing it to the utopian traditional narrative of a composition that exists outside of time and of the contingencies of its realisation. He has put it at the very centre of his work, elevated it to an organisation principle, to a generator of experiences: "I don't think we're really interested in the validity of compositions any more. We're interested in the experiences of things." As Joel Chadabe puts it, the use of indeterminacy in Cage's work, points "back", out of the electronic studio and into the liveliness of performance.[16] It's no coincidence that Cage is considered one of the initiators of *Live-Electronics*.

[16] Joel Chadabe. The history of electronic music as a reflection of sructural paradigms. *Leonardo Music Journal*, 16:41-44, 1996

Even if antecedents could be seen even in Cahill's Dynamophone and the subsequent development electronic instruments in the period between the two world wars, live-electronics more specifically indicates a practice driven by the desire to bring onto stage production processes and technologies which at that point (beginning of the '60) where still relegated to the studio. Tape recorders, microphones, sine-wave generators and effects such as ring-modulators entered the stage in compositions by e.g. Stockhausen (*Mikrophonie*), Kagel (*Transition II*) or Lucier (*Music for solo Performer*) to name a few.[17] During the same years ensembles like *Musica Elettronica Viva*, *Gruppo di Improvvisazione Nuova Consonanza* or *AMM* appeared which were, to different degrees, based on a practice of improvisation, thus incorporating performative habits common in other musical traditions, e.g. in jazz.

[17] Peter Manning. *Electronic and computer music*. Oxford University Press, 2013

In the context of computer music, algorithmic practices combined with sound synthesis put the composer in a novel position. In traditional composition, performance had to be waited for in order to actually hear the music (except for the "inner hearing" of the music during the compositional process): possibly there could be a big temporal separation between the writing of the piece and its realisation and listening. The computer radically changed this situation: with the first calculators which at the disposal of musical experimenters there could be still a gap of some hours between the start of the score and synthesis generating programme and its output. But, with the rapid development of digital technologies, the temporal separation between formulation (of the processes' rules) and realisation of a composition grew smaller and smaller, almost closing into a loop oscillating between the actions involved in the formulation or modifications of the program and the actual listening to the sound it produces. Suddenly generative music practices, at least in the studio, began to be interactive.

A this point computer music composers could actually begin to *perform* their music while composing it. Even more, this situation promised and enabled composers to extend their actions and their bodies into the construction of structural aspects of a composition in a completely new way. In particular, rapid evolving possibilities to gain higher-level control of processes (e.g. sequencers) and growing number of control interfaces which could be paired with digital computers (e.g. joysticks), further pushed this evolution forward. Thus, following a similar impulse that led to the live-electronics practice, computer composers saw the space for bringing their studio practice onto stage, to stage their composition performance. Joel Chadabe was one of those first to engage with this situation working on pieces that included an interactive control of the composition and by developing the idea of *interactive composing*. He sees this practice as "a two-stage process that consists of (1) creating an interactive composing system and (2) simultaneously composing and performing by interacting with that system as it functions." Regarding

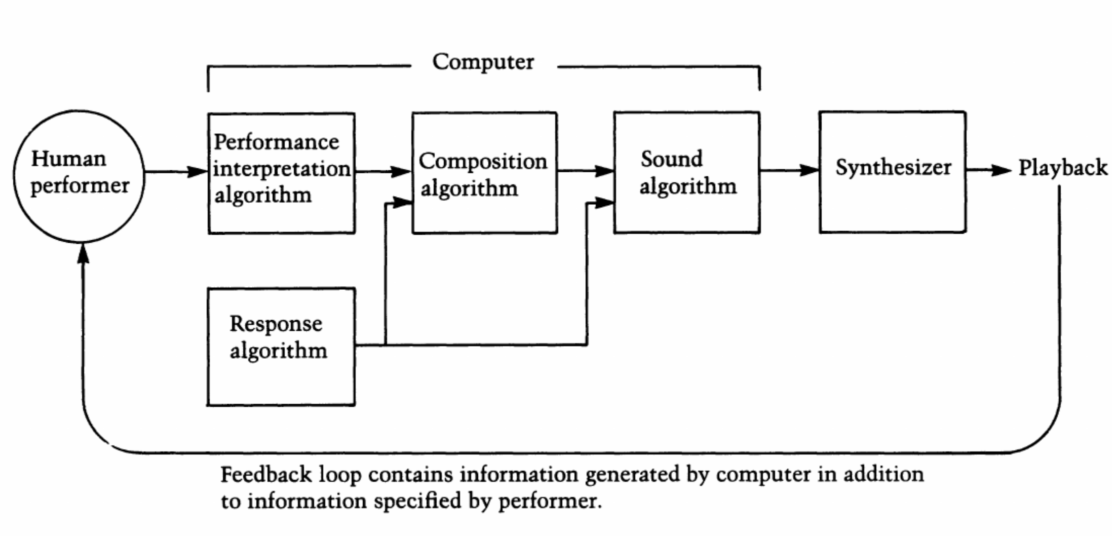


Figure 2.1: Organisation of on interactive composing system. From Joel Chadabe *Interactive Composing: an overview*, Computer Music Journal, 1984, pp. 22-27

his idea of interaction:[18]

> *The performer [...] shares control of the music with information that is automatically generated by the computer, and that information contains unpredictable elements to which the performer reacts while performing. The computer responds to the performer and the performer reacts to the computer, and the music takes its form through that mutually influential, interactive relationship.*

In particular, in order to create this situation, the "interactive composing system operates as an intelligent instrument". Implemented on a programmable computer, this instrument should (see figure 2.1): "Interpret a performer's actions as partial controls for the music. Generate controls for those aspects of the music not controlled by the performer. Direct the synthesizer in generating sounds". I think that the above thoughts are seminal for interactive computer music practice and research that would follow.

A important aspect Chadabe's words appears to be the mixture or, maybe more appropriately, the collision of roles, practices and disciplines that becomes evident in his words. Suddenly the boundaries of the composer's and performer's roles are blurring and in many cases overlapping: the composer performs his composition and the performer composes while performing. The composition is at the same time an instrument. Composers/musicians/performers have to programme and construct their instruments: they are also a bit engineers. This mixture of different, and sometimes contrasting, concepts will on the one hand contribute to a sort appropriative character of computer music (present already from its beginnings): themes,

[18] Joel Chadabe. Interactive composing: An overview. *Computer Music Journal*, 8(1):22-27, 1984

technologies and ideas from the most different disciplines find their way into the discourse around and in computer music keeping it diverse and thus lively. On the other side, especially due to the mixing with other musical practices, this situation will hinder a clear definition of the field still lacking today.

But, what is central in Chadabe's formulation is a fundamental tension that is generated by the juxtaposition of an understanding of interaction as *mutual influence* of performer/composer and the computer music system and the notion of the latter as an instrument. On the one hand, an instrument is a tool that has to be used, the means to achieve something by being employed in a specific way: it is required and expected to produces an output which is consistent. On the other hand a situation of mutual or shared control presupposes an independence of the involved entities in that both would have the capacity to receive external input and to take decisions and act according to some internal (possibly evolving) mechanisms: both actors are expected to be able to take and exert control and none is subordinate to the other. I believe that these two perspectives on computer music systems ascribe qualities to them which are qualitatively opposing. Chadabe tries to build a bridge between them when he attributes an *intelligence* quality to the instrument; but what he actually means is a capacity of the computer system to *sense*, interpret (correctly) and transpose the performer's input: intelligent means in this context reactive. This tensions shows how computer music systems posed challenges which are difficult to answer with the traditional musical notions and roles of the involved elements: performer, instrument, score and composer do not exactly match the situation enacted by computer music, especially when it comes to interactive computer music. But, in retrospect, an uncharted space can be seen spanning between those opposing concepts, a space in which composition could extend into: the composition of interactive relationships.

With the development of the interactive dimension, computer music contributed to a merging with live-electronic practices that were already developed. Due to the flexibility and growing possibilities offered by personal digital computers, these rapidly substituted analog equipment in live-electronic contexts. But, as an effect, computer music systems, especially in connection with performative practices, have been more and more pushed towards an instrumental perspective. This angle has been adopted by most of the researchers and composers until today. Even if a "special" dual nature of carriers of both the notions of instrument and score, of being *composed instruments*[19]

[19] Norbert Schnell and Marc Battier. Introducing composed instruments, technical and musicological implications. In *Proceedings of the 2002 conference on New interfaces for musical expression*, pages 1-5. National University of Singapore, 2002

is acknowledged, the generative character of computer music systems is pushed in the background in favour of more functional view which reduces computer music processes to sound synthesis. When it comes to specify the relation between performer and computer music system, the common scheme followed is that of a linear communication flow which strongly grounds on an instrumental understanding.[20] Information is sent by the performer towards the computer music instrument which interpreters it and produces output accordingly. Such schema (similar as in figure 2.1) can be found in different variations in most of the literature pertaining interaction design in computer music. The under-specification (if at all) of the backward communication channel, from the instrument to the performer, limited to the function of feedback channel that should inform about the system's state, is another indication for the unidirectional and performer-centred perspective.

[20] Agostino Di Scipio. 'Sound is the interface': from interactive to ecosystemic signal processing. *Organised Sound*, 8(3):269-277, 2003

The instrumental condition of computer music systems bears an important characteristic which distinguishes them strongly from traditional acoustic instruments. A distinction can be made between the sound generating part and the set of control mechanisms employed for regulating their parameters. A simple oscillator can be controlled and "played" for example through a keyboard-like interface or a "machine-like" interface with knobs and faders or a touchless interface as the *Theremin* or the proximity-sensitive antennas Joel Chadabe uses in his piece *Solo*. Any musical instrument could be separated in a sound generator and a *performance device*, the interface with which the instrument can be played, and a link between them[21]. In all acoustic instruments the performance device is a structural part of the sound generating mechanism of the instrument, whereas in a typical computer or digital instrument it is not. That means that any performance device ranging from traditional keys and knobs to sensors of any kind can be attached to any of those digital instruments. So, as it is not anymore "given" by the instruments chosen for the composition, the choosing or the development of the performance device and the specification of the link between interface and sound generator becomes part of the compositional process itself, in accordance to the addressed musical context and the musical and performative role the musician or the composer wants to address. That is, the relation between bodily performance and sound generation can be the made subject to re-composition: questions of interface design can and have therefore to be addressed from inside compositional practice.

[21] Joel Chadabe. *Electric Sound:The Past and Promise of Electronic Music*. Prentice-Hall, Upper Saddle River, New Jersey, 1997

With the multiplication of possible interfacing technologies a new research field appears at the intersection of *HCI:*

Human Computer Interaction research and computer music, now commonly defined as *NIME: New Interface for Musical Expression*[22] after the eponymous conference series. While instrument design and interaction design are equated, a plethora of new instruments is developed which explore different ways to connect performer and sound synthesis.[23]

And as new sensing and motion tracking technologies allowing to capture the performer's bodily actions and movements in new ways appear, the fundamental research of interaction is being understood as to find solutions to the problem of how those sensed information enters the computer music instrument. Questions of *mapping*, a general approach which bases on employing functions, or maps, to connect or translate input information to the parameters of the digital instrument, becomes central in many applications centred on gestural input (or control).[24] Even if increasing the complexity of the mapping function seems to result in more engaging situations,[25] it remains true that within such approach, the computer music system remains a deterministic machine completely under the control of the user: the *generative potential* of computer music system is here completely suppressed.[26]

An alternative approach consists in assigning to the computer music system the capabilities of analysis of the input information: the result of that analysis is then the input to the sound producing process. That is, the computer is re-interpreted and implemented as as a sort of *listener* and *interpreter* of the sensed input.[27] Especially from Rowe's work it can be understood that here interaction is typically "been predicated on the technical acquisition of information about the momentary relationship of action (body) and reaction (system)": the proposed model of interaction "draws from human conversation".[28] A similar and extremely sophisticated example in this direction is the work of George Lewis on his composition *Voyager* which employs a "virtual interactive computer-driven, improvising orchestra that analyzes an improvisor's performance in real time, generating both complex responses to the musician's playing and independent behavior arising from the program's own internal processes."[29] Peculiar to this work, which bases on a very idiomatic conception of musical performance rooting in the free-jazz practice and culture, is the author's perspective on the relationship between musician and system: "there is no built-in hierarchy of human leader/computer follower: no 'veto' buttons, pedals or cues".

The above examples are only a few taken to exemplify a field of research which is very active, diverse and

[22] http://www.nime.org/, accessed on 03/11/2017

[23] Sergi Jorda. *Digital Lutherie Crafting musical computers for new musics' performance and improvisation*. PhD thesis, Department of Information and Communication Technologies, 2005

[24] Claude Cadoz and Marcelo M. Wanderley. Gesture - music. In M.M. Wanderley and M. Battier, editors, *Trends in gestural control of music, Paris, IRCAM/Centre Pompidou*, 2000; Marcelo M. Wanderley and Philippe Depalle. Gestural control of sound synthesis. *Proceedings of the IEEE 2004*, 92(4):632 - 644, April 2004; Dylan Menzies. Composing instrument control dynamics. *Organised Sound*, 7(3):255-266, 2002. ISSN 1355-7718; and Andy Hunt, Marcelo M Wanderley, and Ross Kirk. Towards a model for instrumental mapping in expert musical interaction. In *Proc. of the 2000 International Computer Music Conference*, pages 209-211, 2000

[25] Tellef Kvifte. On the description of mapping structures. *Journal of New Music Research*, 37(4):353-362, 2008

[26] Joel Chadabe. The limitations of mapping as a structural descriptive in electronic instruments. In *Proceedings of the 2002 conference on New interfaces for musical expression*, pages 1-5. National University of Singapore, 2002

[27] Robert Rowe. *Interactive music systems: machine listening and composing*. MIT press, 1992; and Todd Winkler. *Composing Interactive Music*. MIT Press, 1998

[28] Garth Paine. Interaction as material: The techno-somatic dimension. *Organised Sound*, 20 (1):82-89, 2015

[29] George E. Lewis. Too many notes: Computers, complexity and culture in "voyager". In *Leonardo Music Journal*, volume 10, pages 33-39, 2000

encompassing very different concepts what interactivity could or should be. Also considering the broader context, terms like control, instrument, influence, sensing etc. mix in the discussion contributing more to a loss of focus in what is actually intended by interactivity: a step back is needed. A critical look at the majority of those practices reveals the dominating model of interactive system as that of a reactive or responsive system.[30] While, if its meaning would be taken literally, from the Oxford English Dictionary (2000):

> *The prefix inter- [meaning] Between, among, mutually, reciprocally. Interact [meaning to], act reciprocally or on each other Interaction a noun, [meaning to] blend with each other*

Without going into questions of etymology, also the definition implied by the previously cited formulation by Chadabe, which arises from praxis, refers to a different situation. In particular when confronted with qualities of the systems they implement or refer, most of the approaches fail in generating a situation of mutual influence of reciprocity and implicitly fall into paradigms of unidirectional control-effect flows.

Drawing ideas from *cybernetics*, the transdisciplinary scientific discipline which studies the structure and behaviour of regulatory systems, the communication between performer and computer music system is formulated differently. Breaking the unidirectional relationship and transform it into mutually influential, a *closed loop* of communication and influence appears now as the essential basis for interaction. In particular Bongers sees the failure of typical approaches to interaction in realising this closed loop in the missing attention towards the feedback channel from system to performer: it lacks a proper specification and is not actively employed.[31] Bongers sees the solution in providing "a level of *cognition*" to the computer system.[32] Apart from the maybe naive and schematic concept of human perception and cognition, it is interesting to note how in this model (see figure 2.2) the solution of the problem is to let the computer undergo another step towards "humanisation". In order for the computer system to properly interact with a human it has to "work" and "think" like a human. What can be seen in Bonger's approach, is an important change in the discourse about interaction in computer music: in order to build interactive systems that have those qualities it is necessary to understand how human cognition functions: *cognitive sciences* now enter the field. The term cognitive sciences defines a highly interdisciplinary research field which studies

[30] Garth Paine. Interactivity, where to from here? *Organised Sound*, 7(3):295-304, 2002

[31] Jon Drummond. Understanding interactive systems. *Organised Sound*, 14(2):124-133, 2009

[32] Bert Bongers. Physical interfaces in the electronic arts. In M.M. Wanderley and M. Battier, editors, *Trends in gestural control of music, Paris, IRCAM/Centre Pompidou*, pages 41-70. IRCAM-Centre Pompidou, 2000

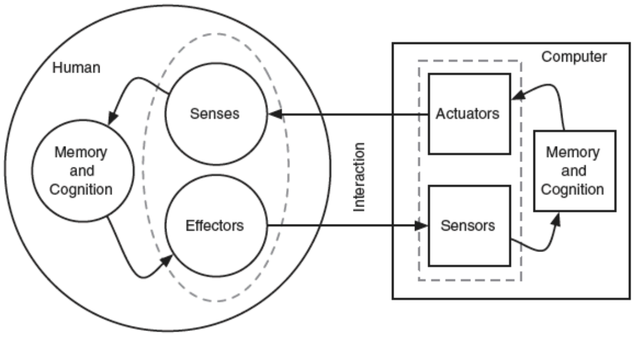


Figure 2.2: B. Bonger's model for Human-Computer interaction. Graphic taken from: Jon Drummond. Understanding interactive systems. *Organised Sound*, 14(2):124-133, 2009

the mind and its processes: a field in which psychology, philosophy, neurosciences and artificial intelligence cross. These disciplines were already influencing of *HCI* years before Bonger's publication. As an example, Don Norman's influential works in HCI draw from the field of psychology and in particular from Gibson's theories of of ecological psychology.[33]

Therefore, it seems clear that, in order to create interactive situations or instruments, questions regarding what *interactivity* actually means and what it affords have to be asked. What do we mean by "mutual" interaction? How could such mutuality be concretely addressed and generated? Are there other formulations of interaction and interactivity? In search for answers, turning to cognitive sciences it becomes clear: in order to shape interaction between humans and computers a theory is needed that addresses what interaction means to us, what role it plays in our perception and cognition and what role the body plays in it.[34] The Embodiment cognition theory offers such perspective.

[33] Donald A Norman. *The psychology of everyday things.(The design of everyday things)*. Basic Books, 1988

[34] Dag Svanæs. *Understanding interactivity: steps to a phenomenology of human-computer interaction*. PhD thesis, Norges teknisk-naturvitenskapelige universitet, 2000

2.3 Embodiment

The roots of *embodiment* theories may be traced back to philosophy and in particular to *phenomenology*. Phenomenology refers to the method developed by philosopher Edmund Husserl of finding the essentials of consciousness or of perception. While focussing on those typically subjective aspects, the method follows indicates a path of *reduction* that would lead to the "thing itself". What is observed should be freed from possibly all prejudices and pre-formed conceptions which could distort the image of the observed phenomenon. Phenomenlogy attempts a sort of "objectification of the subjective" and it does so not by trying to eliminate the latter. Instead it puts at the very centre of a systematic reflection about the world "as we live it", that is as we perceive and experience it. One of the central aspects of this position is that it stands in contrast to an image of the the world as a collection of objects and relations between them detached from the subject as in the Cartesian methodological tradition: the subject might gain knowledge about the world only though an abstract, immaterial reasoning process. In its core phenomenology calls for an alternative worldview which surpasses dualistic body/mind, reason/matter, theory/practice perspectives, which establish the primacy of one over the other.

Heidegger's works develop phenomenology further. He does so with a critique of a tendency towards abstraction he sees implicit in Husserl's thought. For Heidergger, Husserl places experience *in the head* thus retaining a sort of "mentalistic" model of perception and indirectly re-affirm a primacy of theory (the abstract) over practice therefore contradicting the roots of the phenomenological method. He holds that experience is something that happens "in the world". In his major work *Being and Time*[35], he argues that we gain access to world through our practical involvement with it; and further, the relation with the world we construct does not base on pre-formed *mental images* or *models* of it. We engage with the world through what he calls the *ready-at-hand*, objects which do not appear to us as such but that we use with reflecting on them: the example he uses to explaining this concept is that of our use of a hammer in the act of hammering. In that situation the tool is an extension of our body, it does not have a separate nature, it almost disappears as we are engaged with the action. But, it is in the event of a *breaking down*, e.g. the hammer doesn't work properly anymore, that the object is suddenly recognised and presents itself to our perception it becomes *present-at-hand*. But this is not just a revelation of the object, it is the moment in which the object comes into existence. The very ontological structure of the world is therefore not pre-given, but arises through interactions implying embodied actions and their breaking down. The importance of his thought is acknowledged in the field of to HCI: for example Winograd and Flores adopted these views in contrast with the dominating models (at that time, '80) which were influencing computational theories of cognition circulating in computer science.[36]

[35] Martin Heidegger. *Being and time: A translation of Sein und Zeit*. SUNY press, 1996

But the central philosophical work regarding embodiment is the *Phenomenology of Perception* by Merleau-Ponty.[37] At the beginning of his work he rejects the idea of a perception as passive reception of stimuli. In his view perception is an active process *we perform*: "sense-experience is a vital process, no less than procreation, breathing or growth", i.e. sensations are not a state, but are rather the result as an ongoing process of access to the world

[36] Terry Winograd and Fernando Flores. *Understanding computers and cognition: A new foundation for design*. Intellect Books, 1986

[37] Maurice Merleau-Ponty. *Phenomenology of Perception*. Routledge, 2002

through movement and active use of our senses. Further, "the thing is inseparable from a person perceiving it.... To this extent, every perception is a communication or a communion", in opposition to a view (popular in psychology and computational cognitive sciences) where the brain functions as a processor of "data" passively received by the senses. Not only for Merleau-Ponty there is no perception without action, but perception and the "information processing" (the cognition) function of the brain cannot be considered separately, they are intertwined. The nexus of this interconnection is the body and therefore a theory of perception is for Merleau-Ponty at the same time a theory of the body. The body occupies in his theory a special place which is not as an object "among the others", in contrast to classical psychology, nor completely internalised into consciousness. Rather it is the body "as lived" or, as he calls it, the *phenomenal body* or *corps propre*. As identified in Dreyfus' analysis three aspects of *embodiment* contribute to the construction of the phenomenological body: the physical embodiment of a human subject's body having a specific shape; the second is the set of bodily skills developed and acquired by the subject; and the third is the cultural and social "skills" gained in as the subject is embedded in a cultural world.[38] The *phenomenal body* is in itself not static, but rather a dynamic entity, equipped with the structural flexibility that allows us to learn and acquire new skills, to adapt to the external world through a sort of active "incorporation", as Merleau-Ponty writes while describing how an organist "learns" a new organ: the new instrument becomes part of the experienced body, extending it.

[38] Hubert L Dreyfus. The current relevance of Merleau-Ponty's phenomenology of embodiment. *The Electronic Journal of Analytic Philosophy*, 4:1-16, 1996

Grounding on Merleau-Ponty's highly influential work, theories of embodiment have been object of research and have been further developed and sharpened in different ways in the context of philosophy and cognitive sciences. In particular, Varela, Thompson and Rosch, state in their proposition of an *enactive* cognition theory:[39,40]

> *By using the term embodied we mean to highlight two points: first that cognition depends upon the kinds of experience that come from having a body with various sensorimotor capacities, and second, that these individual sensorimotor capacities are themselves embedded in a more encompassing biological, psychological and cultural context.*

[39] Eleanor Rosch, Lydia Thompson, and Francisco J Varela. *The embodied mind: Cognitive science and human experience*. MIT press, 1991

[40] Here the term *sensorimotor* refers to the coupled sensory (the set of sense and their physiological mechanisms) and motor (the set of all movement actuators in the human body) systems.

A stress is thus put on the embeddedness or *sitatedness* of cognition which directly arises from the assumption that perception and cognition are interrelated and determined by action and interaction with the physical world. Knowing is thus situated in the physical or social or cultural context, in which the action takes place. Andy Clark develops this even further: in his thought cognition is emergent from "continuous reciprocal causation", that is from the "continuous, mutually modulatory influences linking brain, body, and world."[41] He sees cognition and the mind body as extending through its continuous interaction into its environment, an "extended mind".[42]

Embodiment is thus, following these thoughts, strongly linked to interaction. More precisely, what we mean with interaction is a continuous exchange with the world we are engaging with and is the basis not only of our perceiving but also of our understanding of it. Interaction is thus shaped, performed and sensed by our body, it is embodied. The importance of embodiment for the HCI field has been recognised in particular by Paul Dourish who set out to define an "embodied interaction". Taking into account the phenomenological approach to perception and the developments in the fields of social and tangible computing, Dourish tries to develop an approach to interaction design which bases not only on the essential physical and bodily aspects of it, but also addresses the social and cultural context interaction is embedded into.[43]

In the context of computer music, embodiment has been widely understood in relation to an acknowledged lack of bodily presence offered by electronic music and computer music performance practices.[44] This perspective largely bases on an idealised view of "traditional" musician's practice in the context of classical music or "instrumental" music in general (jazz, rock, pop etc.). Confronting these practices with those common in computer music, a different, lesser bodily involvement of the musician/performer is evident: this difference is seen as origin of an *expressive* problem inherent in electronic music.[45] That is, simply put, as computer music performance lacks bodily engagement it is less expressive: the theme of embodiment, or the lack thereof, is taken as the core reason in this respect. Expressivity becomes a central theme in computer music interaction design: interactive instruments and interfaces are sought through which the musician could enter a more embodied relationship with the sound the computer music system produces: these instruments would therefore allow for an enhanced musical expression.[46] This strand of development is strongly influenced and fuelled by music cognition research, in particular by the work of Rolf Inge Godøy on "Motor Mimentic Cognition" and Marc Leman on "Embodied Music Cognition"[47] in the context of systematic musicology. Not only music production and performance (the model here is again traditional acoustic music) is

[41] Andy Clark. *Being there: Putting brain, body, and world together again*. MIT press, 1998

[42] Andy Clark and David Chalmers. The extended mind. *Analysis*, 58 (1):7-19, 1998

[43] Paul Dourish. *Where the Action is: The Foundations of Embodied Interaction*. The MIT Press, 2001

[44] Bob Ostertag. Human bodies, computer music. *Leonardo Music Journal*, 21:19-23, 2006

[45] Michael Gurevich and Jeffrey Treviño. Expression and its discontents: toward an ecology of musical creation. In *Proceedings of the 7th international conference on New interfaces for musical expression*, pages 106-111. ACM, 2007

[46] Jin Hyun Kim and Uwe Seifert. Embodiment and agency: Towards an aesthetics of interactive performativity. In *Proceedings of the 4th Sound and Music Computing Conference*, pages 230-237, 2007; and Garth Paine. Towards unified design guidelines for new interfaces for musical expression. *Organised Sound*, 14 (2):142-155, 2009

[47] Marc Leman. *Embodied music cognition and mediation technology*. MIT Press, 2008

seen here as intimately connected to embodied perception in the sense that bodily involvement is a necessity: but also music reception implies a bodily engagement as "a process of incessant mental re-enactment of musical gestures"[48]. *Musical gestures* are in this framework considered the vehicle through which it is "performed and perceived" which "can be directly felt and understood through the body, without the need of verbal descriptions"[49]. As a consequence, gestures are therefore understood as a fundamental "ingredient" computer music interfaces should be able to sense and transpose or map into sound synthesis parameters.[50] That is, bodily gestures are the way to enable a more embodied perception of electronic and computer music rather than just allowing a "disembodied, mentalesque engagement"[51].

I am critical towards the former understanding and "use" of embodiment and the underlying assumptions these approaches imply. As the last reported statement about a "disembodied" musical cognition exemplifies, those approaches to embodiment, often only implicitly, assume that electronic music in general afford a disembodied engagement as being "mental" or "abstract". Such assumptions reintroduce a division between the mental and the bodily and are thus in opposition with the most important direct consequence of the concept of embodiment (in some way already contained in the foundations of phenomenology): the overcoming of the mind/body division. This basic contradiction can be read also from Leman's most important work, "Embodied Music Cognition and Mediation Technology". In particular, "Leman's account for an action-oriented approach, based on the notion of corporeality is, in fact, supposed to overcome the problem of dualism, but its aim is to provide an epistemological foundation for bridging the gap between musical mind and matter intrinsically contradicts its own assumptions"[52] by falling back into a dualistic perspective. Further, there seems to be a strong underlying assumption that the paradigms of traditional acoustic instrumental practices should be equally applied to computer music instruments: an assumption which is not really fully justified. There are of course good reasons in applying those paradigms: instrumental music has a long tradition and underwent a long evolution and therefore much could be "approriated" or learnt from it. Computer music practice might however as well develop other equally valuable paradigms which afford a different performative situations. Lastly, even if musical *expression* is at the core of much of the research and development in interactive interfaces for computer music, it is still not entirely clear what its contents should be, e.g. communication,

[48] Rolf Inge God. Motor-mimetic music cognition. *Leonardo*, 36(4): 317-319, 2003

[49] Marc Leman. Music, gesture, and the formation of embodied meaning. In Rolf Inge Godøy and Marc Leman, editors, *Musical gestures: Sound, movement, and meaning*, pages 126-153. Routledge New York and Abingdon, England, 2010

[50] Marcelo M Wanderley. Gestural control of music. In *International Workshop Human Supervision and Control in Engineering and Music*, pages 632-644, 2001; and Eduardo Reck Miranda and Marcelo M Wanderley. *New digital musical instruments: control and interaction beyond the keyboard*. AR Editions, Inc., 2006

[51] Marc Leman and Rolf Inge Godøy. Why study musical gestures. In Rolf Inge Godøy and Marc Leman, editors, *Musical gestures. Sound, movement, and meaning*, pages 3-11. Routledge New York, NY, 2010

[52] Andrea Schiavio and Damiano Menin. Embodied music cognition and mediation technology: a critical review. *Psychology of Music*, 41(6):804-814, 2013

meaning, emotion, articulation or "style". And further, it is not entirely clear if expression is at all a category relevant to contemporary music practices at large, it surely is not in the works of Cage, or Xenakis, or Brün or Morton Feldman.[53]

Another understanding of embodiment in computer music is that of an *emboding of* something and draws from Don Ihde's concept of the *embodied relations*.[54] Ihde's ideas address relations between humans and technology. In particular relatioships where artefacts become means through which the world is perceived, interacted with and encountered. These relations may be embodied in that the technology does not become evident to perception, rather it is a transparent means through which the environment is explored. Those are technological objects (his examples include glasses, hearing aids, a blind person's cane, but also a hammer) with which a sort of symbiosis is enacted in which our perception extends into the artefact itself. In this sense Ihde's work is clearly rooted in Merleau-Ponty's work, in particular in the idea of the embodied perception *extending* into the technological artefact, which at that moment becomes part of our body. Approaches employing this understanding to create interactive computer music environments that attempt to create the conditions for an interaction afford this kind of embodiment to occur.[55] An interactive instrument is thus devised that can completely dissolve in the interaction with the performers, being fully penetrated by their bodies, inhabited like a suit and embodied in their perception. The utopia lurking behind such approach is again that of the total control of the instrument by the musician; a direction which is, in my opinion, again in opposition with the idea of an interaction between mutually influential entities. In this case, one of the entities is "absorbed" by the other which takes complete control over it. On the contrary, if a mutuality has to be reached the "other" the counterpart, seems to be very visible, perceivable and almost graspable in order to allow for such a relationship.

So how is the concept of *embodiment* relevant to this context of computer music? How could it be effectively employed in addressing the idea of a mutual interrelation that I am placing at the core if this interaction model? The difficulty is that the theory of embodiment describes properties of human perception and cognition which are *inherent*: that means, embodiment is a *permanent mechanism* of our perceptual system, and therefore something like *disembodiment* could not really exist. In particular it seems difficult to talk about an interface or computer music system or even a kind of sound which could in some

[53] Michael Gurevich and Jeffrey Treviño. Expression and its discontents: toward an ecology of musical creation. In *Proceedings of the 7th international conference on New interfaces for musical expression*, pages 106-111. ACM, 2007

[54] Don Ihde. *Technology and the lifeworld: From garden to earth.* Indiana University Press, 1990

[55] Garth Paine. Interaction as material: The techno-somatic dimension. *Organised Sound*, 20 (1):82-89, 2015; Gerhard Eckel. Embodied generative music. In Deniz Peters, Gerhard Eckel, and Andreas Dorschel, editors, *Bodily expression in Electronic Music*, chapter 10, pages 143 - 151. Routledge, 2012; and Gerhard Eckel and David Pirrò. On artistic research in the context of the project embodied generative music. In *Proceedings of the 35th International Computer Music Conference*, pages 541-544, Montréal, 2009

way be disembodied in itself. At the core of the reasoning about embodiment lies a perspective that is deeply rooted in the perceiving subject: it seems therefore inappropriate to identify an "external" object that has an ontological quality of being disembodied *a priori* independently of the subject. That is, as there is actually no possibility for a disembodied relation to occur between human and technological artefact, could this mean that embodiment is actually entirely meaningless for interaction design? As Dourish puts it:[56]

> *If we are all embodied, and our actions are all embodied, then isn't the term embodied interaction in danger of being meaningless? How, after all, could there be any sort of interaction that was not embodied? What I am claiming for embodied interaction is not simply that it is a form of interaction that is embodied, but rather that it is an approach to the design and analysis of interaction that takes embodiment to be central to, even constitutive of, the whole phenomenon.*

That is, the great value the concept of embodiment for interaction design is that it reveals aspects that should be put at the very centre of such design, explicitly acknowledging and centring on the dimensions on which embodiment builds e.g. the qualities of the physical body and of the relations we can enter with the world through it.

At this point, before continuing, I think its useful to look back and understand how we happen to have arrived here. We found that, in order to create a situation of mutual influence between a performer and a computer music system, venturing into theories of cognition and perception would provide a better understanding of *how* that influence is exerted and received. In particular the interest lies in finding a better and stronger specification of the "feedback channel", the connection that goes from the system to the performer. We look at how human cognition and perception "functions" for the purpose of "equipping" such system with the similar basic capabilities by, to some extent, imitating and "mirroring" such functions in the computer system. On this path we encountered the theory of embodiment which seems apt the be a basis for such an endeavour, in that it explicitly puts the body and its continuous interactions with the world at the centre of cognitive functions. What is needed at this point, is a perspective that focuses on the qualities of such interactions; qualities that could be "exploited" by a computer music system to enter in a continuous, mutual

[56] Paul Dourish. *Where the Action is: The Foundations of Embodied Interaction*. The MIT Press, 2001

interaction with the performer.

Interesting is at this point an exchange philosophers Deniz Peters and Alva Noë have on the pages of the book "Bodily expression in Electronic Music" that has been published in the context of the Embodied Generative Music" project.[57] The discussion is around the question if it would be possible to think of a disembodied electronic music. The question is answered negatively by both by following similar paths: embodiment always centres on the perceiving subject, but they stress the fact that this is not a just passive reception of "information". The crucial point is, recalling Merleau-Ponty's *phenomenology*, that this perception is active in the proper sense of an activity that is performed. Alva Noë, in particular in his work "Action in Perception" stresses an opposition to a "projective" idea of perception, in which our senses are subject to external stimuli that are then processed by our cognitive system: from this perspective the world we live in is also removed from us, separated. He instead endorses the idea that we are in continuous "contact" with the world. Proposing the paradigm of *touch* for describing perception, he argues that "seeing is like touching", taking an object in the hands moving it around to feel it, it form, weight and surface. In other words, perceiving and bodily movement are interrelated: moving and acting on something, we produce variations in that object which we then reconstruct and integrate in perceiving that object: "to perceive is to exercise one's skillful mastery of the ways sensory stimulation varies as a result of bodily movement".[58] Thus, the very act of listening to a sound requires an *action of perception* and this action is a deeply bodily one. Sound *is embodied* in the sense that perceiving implies bodily interaction with it. Perception is an activity, a process of bodily interaction with the world, an *enactive* process.

[57] Alva Noë. What would disembodied music even be? In Deniz Peters, Gerhard Eckel, and Andreas Dorschel, editors, *Bodily expression in Electronic Music*, chapter 3, pages 53 - 60. Routledge, 2012; and Deniz Peters. Touch. real, apparent, and absent: On bodily expression in electronic music. In Deniz Peters, Gerhard Eckel, and Andreas Dorschel, editors, *Bodily expression in Electronic Music*, chapter 1, pages 17 - 34. Routledge, 2012

[58] Alva Noë. *Action in Perception*. The MIT Press, 2004

2.4 Enaction

The term *enactive approach* and the concept of *enaction* refers to the perspective towards cognition Varela, Thompson and Rosch elaborated in their book "The Embodied Mind"[59]. An interesting aspect of this approach is that it draws ideas from research areas as distant as biology, cognitive sciences, neurology, psychology and philosophy and attempts to construct an unifying theory of cognition. But, the fundamental roots still lie in Merelau-Ponty's phenomenology, in the idea of perception as action and in particular in his theory of embodiment. In their words, the enactive approach views "cognition as *embodied action* and so recovers

[59] Eleanor Rosch, Lydia Thompson, and Francisco J Varela. *The embodied mind: Cognitive science and human experience*. MIT press, 1991

the idea of embodiment". From this perspective embodiment "encompasses both the body as a lived, experiential structure and the body as the context or milieu of cognitive mechanisms", i.e. as the locus both of the coupled sensory-motor system acting on the world and of higher cognition functions. But, the concept of *enaction* goes further:

> *the enactive approach consists of two points:*
> *(1) perception consists in perceptually guided action and*
> *(2) cognitive structures emerge from the recurrent sensorimotor patterns that enable action to be perceptually guided.*

Thus, as in Merleau-Ponty's phenomenology, perception is as an action a perceiving subject performs. As a consequence of this actions, the local world the subject is embedded in, will change and thus, in order to study perception, it is not possible anymore to refer to a pre-given and invariant external world. The centre of such study has to become the sensory-motor structure of the perceiver, how it is embodied. The enaction approach asks how action is actually *guided* by the subject. More precisely, the interest of the enactive approach lies in understanding the principles of the linkage of the sensory and motor system, that is how action is influenced by the continually changing sensory information. Importantly, perception is here therefore not just situated and embedded in its environment, but it contributes to its enactment: "the organism both shapes and is shaped by the environment". It is a continuous process of action/change/sensing taking place between the subject and the environment. When this process results in patterns, recurring recognisable temporal structures, then the subject can form cognitive structures which allow to act on the link between the sensory and the motor system, thus to guide perception.

Enaction therefore proposes an approach to cognition which is fundamentally opposed to any kind of "representationist" approaches that view cognition as a sort of "information processing" of data provided by a pre-given external world. Instead, enaction views cognition is a highly dynamical, temporal process arising from a continuous embodied action in an environment. The crucial aspect is that from the enactive perspective, perceiver and environment are two coupled and mutually interacting systems. Not only action is necessary, but more fundamentally, *being acted upon* that is action from the environment is necessary for an entity in order to perceive and construct cognition structures. Essentially "living beings and their environments stand in relation to each other through mutual specification or co-determination."[60] This co-determination of organism and environment is central to the concept of enaction.[61]

[60] Eleanor Rosch, Lydia Thompson, and Francisco J Varela. *The embodied mind: Cognitive science and human experience*. MIT press, 1991

[61] Evan Thompson. *Mind in life: Biology, phenomenology, and the sciences of mind*. Harvard University Press, 2010

The concept of enaction has received little attention in the context of computer music. Isolated examples mostly take the concept to frame interface design towards an approach acknowledging perceptual sensory-motor coupling, but remain in a merely instrumental perspective. The aim is the development of a *transparent* interface that, by tapping into enactive qualities of perception, would allow a more *intimate control* of the computer music instrument by the performer.[62] As I tried to explain before, the central idea of the enactive perspective is that of a structural coupling between two systems, in the present case the human performer and computer music system, which engage in a mutual interaction: an exchange which bases on a continuous sensory-motor engagement. Further I believe that this image fits the ideal of interaction I have been aiming at. In order to perceive the computer music system, the performer has to both continuously sense it and act on it: the variations of the system's responses as a function of the performer's movements or action, if exhibiting recurring patterns, would allow cognition to "resonate" into a coherent image, it would allow to *attune*[63] to it. The paradigm of touching as used by Alva Noë might be useful here: to perceive the system the performer has to touch it, move it, weight it. A useful concept in this respect is *resistance*[64]. Meaning that the system should allow an interaction in which a resistance is felt while being contact; a resistance towards the performer's actions, that signals that "something is there" that can be explored and that would reveal the "form" of the system itself and its characteristics.

[62] David Wessel. An enactive approach to computer music performance. *Le Feedback dans la Creation Musical,Lyon: Studio Gramme, France*, pages 93-98, 2006

[63] The concept of *attunement* is here borrowed from Merelau-Ponty and then reprised by Thomson in *"Mind in Life"* as it fits well the idea of resonance. Though, I will not give a complete definition of the term here.

[64] Newton Armstrong. *An enactive approach to digital musical instrument design*. PhD thesis, Princeton University, 2006

Another concept which could be useful in further characterising the situation, which pairs well with resistance, is that of *affordance*. The concept has been introduced by psychologist J.J.Gibson in his *ecological approach* to psychology.[65] Within this theory he elaborated a perspective on perception in which the role of the environment is set as central. In the ecological approach, the environment offers opportunities for interaction relatively to the sensory-motor capabilities of the perceiving subject. Affordances are thus ecological features of the world of things that elicit actions: a good example is how a mug's handle affords a specific motor action for grabbing the mug. In a way, affordances are the "motor sense" of objects in the environment.

[65] James J Gibson. *The ecological approach to visual perception: classic edition*. Psychology Press, 2014

Returning to the question of how a computer music system should then be shaped in order to be interactive in the sense described before, in terms of an enactive approach, we could say that the system should, at the same time:

- Present *resistance* towards the performer's actions, showing that there are limits or constraints in which the interaction can take place. Therefore also affirming its boundaries and its identity as a perceivable object.
- Offer *affordances* by eliciting the perceiver's sensory-motor system. Returning to the touch metaphor, it provides and shows the handles having the correct dimensions and shape for being grasped.

So how can these qualities be realised? To address these qualities, the computer music system should *attune* to the performer's perception and cognitive system's structure. And therefore, in order to elicit a sense of resistance and affordance, it has to base on a *model* that in its functioning resonates with the human's enactive perception and cognition process. Fortunately, within the theory of enaction such model can be found in the definition of *agency*.

The enactive approach, through the year-long collaboration of Francisco Varela with Humberto Maturana culminating in their book "The Tree of Knowledge"[66], has strong roots in biology and neurosciences. Their research focused on finding the biological roots of understanding, that is, on describing the basic mechanisms which are the foundations of knowing and cognition in living beings. As cognition is an essential quality of living organisms, it indirectly is a characterisation of what can be considered a "living entity". This perspective establishes therefore a *circularity* between the concepts of "life" and living organisms and "cognition". In the words of Maturana[67]:

[66] Humberto R Maturana and Francisco J Varela. *The tree of knowledge: The biological roots of human understanding.* New Science Library/Shambhala Publications, 1987

[67] Humberto R Maturana and Francisco J Varela. Biology of cognition. In *Autopoiesis and cognition*, pages 2-58. Springer, 1980b

> *A cognitive system is a system whose organisation defines a domain of interaction in which it can act with relevance to the mantainence of the self and the process of cognition is the actual acting or behaviour in this domain. Living systems are cognitive systems, and living as a process is a process of cognition. This statement is valid for all organisms, with and without a nervous system.*

The former statement also implies that cognition is a process that involves acting, it *is doing*: a perspective that clearly resonates with the enactive theory. Living beings are thus characterised by being agents (to be understood in the Latin sense of *agens*, doer) of cognition. Evan Thompson places the idea of agents at the foundations of enactive theory:[68] the idea of enaction is "that living beings are autonomous agents that actively generate and maintain themselves, and thereby also enact or bring

[68] Evan Thompson. *Mind in life: Biology, phenomenology, and the sciences of mind.* Harvard University Press, 2010

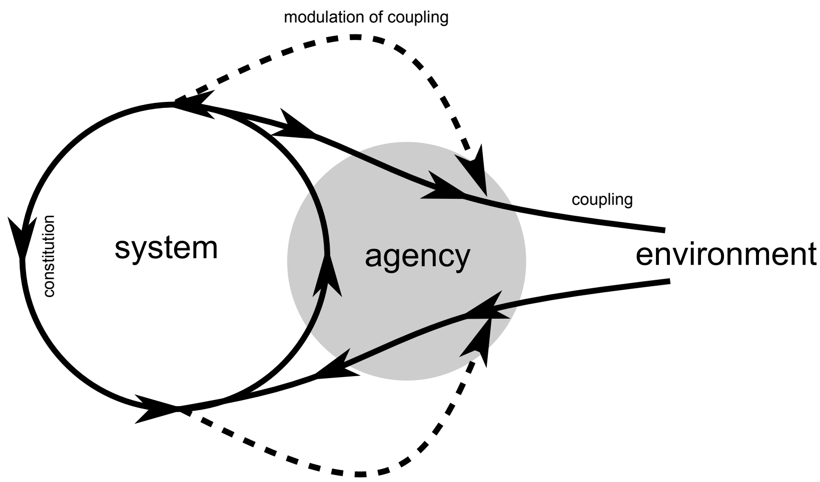


Figure 2.3: Diagram illustrating the definition of agency: redrawn from Xabier E Berandiran, Ezequiel Di Paolo, and Marieke Rohde. Defining agency: Individuality, normativity, asymmetry, and spatio-temporality in action. *Adaptive Behavior*, 17(5):367-386, 2009

forth their own cognitive domains". Further "a cognitive being's world is not a prespecified, external realm, represented internally by its brain, but a relational domain enacted or brought forth by that being's autonomous agency and mode of coupling with the environment." Agency and enaction are thus very closely related and interdependent.

In the first enaction theory, agency is strongly related to the concepts of *autonomy* and the *adaptivity* of the living system. Autonomy designates the the system's ability to *self-organise* and self-specify: it is what Maturana called the *autopoiesis* of the living system.[69] While adaptivity postulates the existence of a *coupling* between the system and its environment and defines the capacity of the systems to regulate this connection with the environment. Adaptivity is a function that calibrates action/perception processes in the agent as a consequence of the external stimuli/reactions. Autonomy is certainly a necessary condition, but only jointly with adaptivity it becomes also a sufficient condition for agency.[70] A more detailed characterisation has been recently provided by Barandiaran and Di Paolo:[71] following this work, agency can therefore be defined through three different (even if interrelated) conditions (see figure 2.3):

69 Humberto R Maturana and Francisco J Varela. Autopoiesis: the organisation of the living. In *Autopoiesis and cognition*, pages 73-135. Springer, 1980a

70 Ezequiel A Di Paolo. Autopoiesis, adaptivity, teleology, agency. *Phenomenology and the cognitive sciences*, 4(4): 429-452, 2005

71 Xabier E Barandiaran, Ezequiel Di Paolo, and Marieke Rohde. Defining agency: Individuality, normativity, asymmetry, and spatio-temporality in action. *Adaptive Behavior*, 17(5):367-386, 2009

1. Individuality: For a system to be an agent, there must be some distinction between the system and the environment. The agent must have clear boundaries and there must exist some clear "relation" between the systems and its environment which identifies it. It is an entity identifiable from the perspective of the environment.

2. Interaction Asymmetry / Source of Activity: This concept is related to an idea of *action*: the agent *does* something, an agent is a source of activity, not

merely a passive receiver of external effects. The idea specifies that the type of coupling between agent and environment is not just one of *reaction*, it is a coupling through which the agent acts by some internal, local and individual mechanisms. This aspect becomes evident the moment in which the agent re-modulates its coupling to the environment from within, therefore breaking the symmetry of two coupled systems.

3. NORMATIVITY / ADAPTIVITY: The coupling with the environment is modulated in order to reach or move the system's state towards a specific *goal*, here called *norm*. This regulation might result in *success* or *failure* in achieving that goal: this is what is defined as the *normativity condition*. E.g. the planetary system cannot fail to follow the laws of gravitation and is therefore not an agent. That is, *failure* or the possibility of is a central characterising quality of agency. The specification of a goal or aim a system should have might seem odd, as the concept can be very dependent of the perspective form which the dynamic of system and environment is observed. What is actually meant here, is that an agent system should tend to maintain *its norm*, meaning it should try to preserve its further activity. The norm is its further existence.

These specification clarifies one important point. An enactive agent is not only both autonomous and coupled to its environment, but, most importantly, it has the faculty to adapt by re-calibrating this coupling. Which means that the system is able to *observe its own state* and perform adaptations which should push that state towards, for its existence, better functioning regions. I believe that this agent quality is fundamental and constitutes an essential and discriminating aspect.

Now we have a characterisation of the fundamental and defining qualities of an agent. As Evan Thompson suggest while writing about the sense of empathy towards another (human) living organisms "we perceive her [...] as a locus of intentional agency and voluntary movement"[72]. That suggests, agency is not only an essential ingredient for an enactive organism, it is also the perceptual quality by which agents recognise and identify each other. So, the idea at this point is to move on and "equip" the computer music system with agency such that the performer would recognise the system as agent with which an enactive interaction is possible. That is, the aim is to realise a system with such perceivable characteristics in the way of behaving in correlation with the actions of the performer, that *agency will be perceived or re-constructed*

[72] Evan Thompson. *Mind in life: Biology, phenomenology, and the sciences of mind*. Harvard University Press, 2010

by a performer through enactive interaction. Essentially, agency reveals as the process which produces the *resistance* and the *affordance* to be perceived as an autonomous and interactive process.

The pressing question is now, how can such system be realised? With which tools and following which formalism? The enactive theory of perception has also roots in the mathematical formalism of *Dynamical Systems*. This will be the language I will use to deal with those questions. The next chapter will provide a short introduction in the theory and use of dynamical systems.

3
Dynamical Systems

Dynamical systems are a mathematical formulation describing the time dependence of an object or an ensemble of objects in a geometrical space: they are constructs which describe temporal evolution. They do so by employing mathematical statements, equations that express how an object will change its state given its present state or the state of other elements in the system. Rules of temporal evolution which act like a "force" on those objects, pushing them to move on a path. Hence the origin of the name, which comes from the greek *Dynamis* (δυναμισ) which means "force".

The above description already shows how dynamical systems could address an enormous variety of phenomena. Any process that has a temporal evolution can, in principle, be expressed in term of dynamical systems. Actually most (if not all?) phenomena we are confronted with have a temporal dimension, dynamical systems are therefore ubiquitous. Does then the term risk to be too unspecific and too broad to actually mean something? If everything in the end is a dynamical system, how is the concept useful?

Yes, it’s true: the phrase "something is a dynamical system" is so indefinite that it actually contains no information about the thing itself. Still, there is something implied by such affirmation which is important to underline. "Something is a dynamical system" means that I look at the thing as a temporal phenomenon, I look at the *temporality* of that thing and that I think that its evolution is its fundamental quality. That phrase pertains less to what that observed thing *is*, it is more an indication of *how* I am looking at it, what kind of perspective I have chosen to examine it. A perspective based on time and interaction. And it is an indication of which language I have chosen to use in formulating my thoughts.

The next section contains a short theoretical and lightly mathematical framing of dynamical systems theory. In this context this part cannot really cover all aspects of the huge field of the mathematical study of dynamical systems: this part is meant just as very short introduction. The next sections will describe how dynamical systems have entered the of research fields of perception and cognitive sciences and further, which approaches to computer music have been influenced by this perspective. This sections are meant to justify my extensive use, later in this work, of formulations based on dynamical systems theory, both in discussing and in realising the thoughts and experiences contained in this work.

3.1 Theory

I will begin this section by attempting the clarify the definition of *dynamical system*, as I understand it here, starting by dissecting the concept into the two[1] terms it is composed of.

Here the term *dynamical* or *dynamic* has to be understood in the meaning mostly common in physics, as to indicate the quality something has by being in motion i.e. by exhibiting some sort of temporal evolution. *Dynamic* is used to denote phenomena showing patterns of temporal evolution at one time which are interrelated to those at different times[2]. In this meaning *dynamic* becomes almost a synonym for time-evolution or pattern of change, referring to the unfolding of events in an continuous evolutionary process.

Most of the phenomena we are confronted with in our daily lives have some dynamic aspect. Simple physical systems, moving objects like a kicked football travelling through the air under the effect of the gravitational and other forces. Or complex social systems in hierarchical organisations or evolving economical structures. Dynamics is a pervasive quality of what we perceive.

The term *system* is used throughout diverse contexts with different meanings and therefore can be very unspecific. Basing on the meaning the word inherits from its greek origin, $\sigma\upsilon\sigma\tau\eta\mu\alpha$, "a whole composed by several parts", this word is used here to denote an identified set of elements linked by mutual connections and interactions. This network of interrelations is responsible not only for the appearance of the set as a whole, but also, in the case of *dynamical systems*, of its evolution. These interactions are responsible of the particular form this unfolding takes, the *behaviour* of the system.

Dynamical systems (or more often the reduced form *dynamics*) not only stand for the time-evolutionary phenomena the world presents us with, but also for the mathematical discipline that attempts to formulate and analyse such phenomena from an abstract, general perspective. This branch of mathematics has a history of almost 350 years:

[1] For a good and complete introduction to dynamical systems theory, I suggest to refer to a more extended treatment as can for example be found in the book by Steven Strogatz. Some examples I report here are taken from that book.
Steven H. Strogatz. *Nonlinear dynamics and chaos: with applications to physics, biology, chemistry, and engineering.* Westview press, 2014

[2] D.G. Luenberger. *Introduction to Dynamic Systems: Theory, Models, and Applications.* Wiley, 1979

it has its origins in physics, but over the time it has spread into various research fields; chemistry, social sciences, biology, communications engineering just to name a few. This lead to the development of a multitude of different mathematical and conceptual tools. But still, all of these, ground on the work and the ideas of its two most prominent fathers:

- NEWTON was one of the main developers of *calculus* (together with Leibnitz) and the inventor of ***differential equations***, the formalism he introduced to study and analyse physical processes. With this tool he formulated the laws of motion and gravitation, and laid the foundations of modern physics. In particular Newton's fundamental second law of motion establishes a relationship between the force F affecting an object of mass m and the acceleration a the object experiences as effect of the force:

$$F = ma \tag{3.1}$$

  As the acceleration is the second derivative of the object's position x with respect to time[3],

$$a = \frac{\mathrm{d}^2 x}{\mathrm{d}t^2} \tag{3.2}$$

  Since then, dynamical Systems have been expressed in terms of differential equations: from the perspective of mathematics, the study of dynamics become almost synonymous with the theory of differential equations.

Differential equations express the dependence of some (physical) quantity on time. More precisely they formulate *how* that quantity will change its value with respect to time, in which way, or how the path of its variation will be shaped.

In order to elucidate these aspects, as an example, we could consider the ideal spring-mass system, a classic example of an ideal, i.e. friction-less system[4]. The system consists of a mass m attached to a spring (see the diagram in figure 3.1). *Hooke's law* states that the force F the spring exerts on the mass is proportional to the elongation or compression x of the spring:

$$F = -kx \tag{3.3}$$

where the coefficient of proportionality k is the spring constant. Following then Newton's law (equation 3.1) the system's dynamics can be mathematically expressed:

$$m\ddot{x} = -kx \tag{3.4}$$

The above describes how the acceleration of a mass m is connected to the force exerted by the spring with spring

[3] Throughout this text and from here on, we will use the overdots notation to denote differentiation with respect to time t: $\dot{x} = \frac{\mathrm{d}x}{\mathrm{d}t}$ and $\ddot{x} = \frac{\mathrm{d}^2x}{\mathrm{d}t^2}$

[4] The term *system* here is used in the acception introduced above. It denotes the set of two elements spring and mass bound together by their mutual interaction.

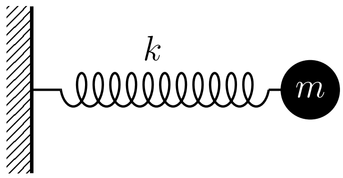


Figure 3.1: The diagram for ten classic spring-mass system

constant k, or, in other words how the velocity v of the mass will change over time under the effect of the force exerted by the spring. Differential equations are thus the mathematical formulations of the laws of change and variations governing a system.

Differential equations where applied in order to mathematically formulate a variety of mechanical problems. And to find "solutions" to those problems, meaning finding explicit mathematical formulae expressing the motion of the involved elements. For example, in the case of the above spring-mass system, the solution describing the masses motion:

$$x(t) = Acos(\omega t - \phi) \tag{3.5}$$

where A and ϕ are parameters dependent on the initial conditions in which the mass was when time "starts", e.g. in which position it is and which velocity it has when starting to observe it. The above equation, as it contains a periodic function *cos* states that the motion of the mass is oscillatory with a fixed frequency ω and is a "solution" as it expresses this motion, that is how the position of the mass changes over time, in terms solely of time passing and of a few constant parameters.

The most interesting problems to address at the time of Newton where in particular those concerning the evolution of the planetary system, the motion of planets and satellites. After Newton, physicists tried in particular to solve the so-called "three-body" problem, to find the laws of motion for three objects of mass m_1, m_2 and m_3 under the reciprocal effect of gravitational forces these exert on one another. Despite the relatively simple formulation and clear problem, it turned out to be *impossible* to solve. In the sense that with the mathematical tools we have developed until now we are not able to formulate solutions to this problem.

The three-body example shows what I think is an essential characteristic of dynamical systems theories. The complexity of a problem meaning the difficulty of understanding it or of finding solutions, is not proportional to the complexity of the formulation. Or, said in another way, dynamical systems theory can provide very simple formulations for very complex problems.

- Poincaré was extremely influential in the development of dynamical system theory in many ways. His greatest contribution was introducing in the late 1800s a completely new way of thinking about those problems. He developed a point of view that asked about the *qualitative* aspects of a system's temporal evolution prioritising these with respect to *quantitative* questions. For example, regarding the mentioned tree-body problem, rather then concentrating on finding a formula mathematically expressing the position of the objects at any time, he would ask "Is the system *stable* as the earth-sun system or will the objects eventually fly off to infinity?"

In order to answer those type of questions he developed a powerful *geometrical* approach with which a system's properties e.g. how it would generate motion or how the temporal evolution associated would appear as figures, images of its behaviour. The qualitative method grounds on a visual understanding of system's behaviour. It bases on the concept of *phase space* that is a geometric space containing all possible states a system might be in: the dynamical system "acts" on this space such that each point in this space, each state, is "pulled" towards another state according to the system's rule of evolution, the differential equations defining it. That is, the dynamical system acts as a sort of *flow* in this space, dragging and pushing states around and thus producing trajectories, *phase trajectories* which geometrically depict the system's behaviour.

The critical point is that this representation of a system's dynamics is *isomorphic* to the system's formulation in terms of differential equations. Meaning that the two representations are equivalent and interchangeable: the visual, geometric approach is not just an "approximation", it *exactly* corresponds to the system.

Before turning to some more detailed examples of the *phase space* geometrical representation approach, some more characterisations and distinctions of the kind of problem I am interested in, seem to be useful.

In the set of problems dealing with differential equations there are two big families that can be distinguished: the first is that of *ordinary differential equations* which involve only ordinary derivatives with respect to time. E.g. the equation for a damped oscillator:

$$m\ddot{x} + b\,\dot{x} + kx = 0 \tag{3.6}$$

is such an equation. In this kind of problems *time* t is the only independent variable. *Partial differential equations* constitute the other category. E.g. the heat equation:

$$\frac{\partial u}{\partial t} = \frac{\partial^2 u}{\partial x^2} \tag{3.7}$$

Here both the time t and space x are independent variables. My focus here is only on ordinary differential equations as I am concerned with the temporal behaviour only.

The most general formulation for a dynamical system as a system of differential equation is:

$$\begin{aligned} \dot{x}_1 &= f_1(x_1, x_2, \ldots, x_n) \\ \dot{x}_2 &= f_2(x_1, x_2, \ldots, x_n) \\ &\vdots \\ \dot{x}_n &= f_n(x_1, x_2, \ldots, x_n) \end{aligned} \tag{3.8}$$

First there is set of variables $x_1, x_2, \ldots, x_n$, which might be chemical concentrations, planet positions or populations of different species sharing the same ecosystem. Their temporal evolution, how these variables will change while time advances, is expressed by the functions $f_1, f_2, \ldots, f_n$. The values of these functions are dependent from, in principle, all other variables in the same system. The number of equations n is the *order* of the system, also called *dimension* (if $n = 2$ the system is second-order an so on).

From the formulation above, the *system* idea as it is understood here becomes clearer. A system is composed by a set of variables whose evolution is interdependent on each other's state. All variables are *coupled*, their evolution being affected and affecting each other. The concept of dynamical system, reveals itself here as one deeply rooted in a perspective of a world of interconnected, *mutually interacting* entities or actors. A world of elements and their interconnections, whose evolution is brought forth by their interaction. I see this perspective as very close to an enactive position.

To note is here that system like in equations 3.4 or 3.6 are formulated differently than in equation 3.8 above as the differential equations involve second derivatives. In most cases however it is possible to resort to a formulation in which only first derivatives are involved. This is typically done with a simple change of variables and by introducing a new variable in the system. For instance, in the case of the simple harmonic oscillator in equation 3.4, introducing the second variable velocity $v = \dot{x}$ the system them becomes:

$$\begin{aligned} \dot{x} &= v \\ \dot{v} &= -\frac{k}{m}x \end{aligned}$$

which is a second order dynamical system of the form of equation 3.8. With the same change of variables equation 3.6 would become:

$$\begin{aligned} \dot{x} &= v \\ \dot{v} &= -\frac{k}{m}x - \frac{b}{m} \end{aligned}$$

Further, considering the three systems:

$$\begin{aligned} \dot{x} &= rx \\ \dot{x} &= x^2 \\ \dot{x} &= sin(x) \end{aligned}$$

another distinction can be made. In the first of the two equation in the right-hand side x appears to the first power only while in the second it appears to the second power and in the third it is argument for a function. The first system is said to be *linear* while the other two are *nonlinear*. Another typical example of a non-linear system is that of the pendulum:

$$\ddot{x} + \frac{g}{L} sin(x) = 0 \tag{3.9}$$

Nonlinear problems are typically (especially when the system more dimensions) very difficult to solve. The main difference is that linear problems, even if they have many dimensions, can be broken apart more easily, each part being analysed separately and then put together again without loosing any insight on the global system: the so-called principle of superposition. This is much more difficult in the case of nonlinear problems: breaking apart is not so easy and mostly impossible. Still, nonlinear system are a class of system which actually is more interesting: most of the processes and phenomena we are confronted in our everyday life are nonlinear. Nonlinearity is the realm of *chaotic* behaviour and complex systems theory: that is, in the world of dynamical systems, the hardest and more often impossible to solve problems.

There is another distinction to be made. The system of the forced oscillator:

$$m\ddot{x} + b\dot{x} + kx = cos(t) \tag{3.10}$$

is different from all the above system in that it contains an explicit dependence on time t. This kind of systems is called *nonautonomous* as opposed to the *autonomous* systems we have looked at until now. The idea behind this distinction is that whereas the latter is self-contained, the former is explicitly dependent on some "external" influence, as in the case of the forced oscillator, an external force. An inference exerted from some kind of mechanism that is not internal to the system itself, but in the environment where the system is. Also these systems can be very difficult to study and bear some commonalities with the nonlinear systems, but in some cases a small "trick", a change of variables might help in finding a better perspective to look at the problem. For example, considering the example above, by letting

$x_1 = x$, $x_2 = \dot{x}$ and $x_3 = t$ we get to the formulation of an *equivalent system*:

$$\begin{aligned} \dot{x_1} &= x_2 \\ \dot{x_2} &= \frac{1}{m}(-kx_1 - bx_1 cos(x_3)) \\ \dot{x_3} &= 1 \end{aligned} \tag{3.11}$$

In order to to clarify the *phase space* idea, some more examples are needed, starting from a simple *first-order* nonlinear dynamical system.

$$\dot{x} = sin(x) \tag{3.12}$$

As we said before, the system produces a *flow*, in this case on a line as the system is one-dimensional. The former equation says that in this system there is a *vector field* on the x axis, each vector being a force pushing and pulling each particular state on that axis towards another. Further where $sin(x)$ is positive that push will result in a growth of x as its derivative would be positive thus indicating a positive slope. If $sin(x)$ is negative then the slope would be negative and therefore x would decrease. The arrows in figure 3.2 depict this vector field. At the points where $sin(x) = 0$, for $x = n\pi$, there is no flow: x therefore remains constant. In general, points in which the flow is 0 are called *fixed points*: the solid dots in the figure are *stable fixed points*, called also *attractors* or *sinks*, as the flow from both directions is towards them: the empty dots are *unstable fixed point* also called *sources* or *repellers*. In any case, these points are very important states for the system, they are points of *equilibrium*.

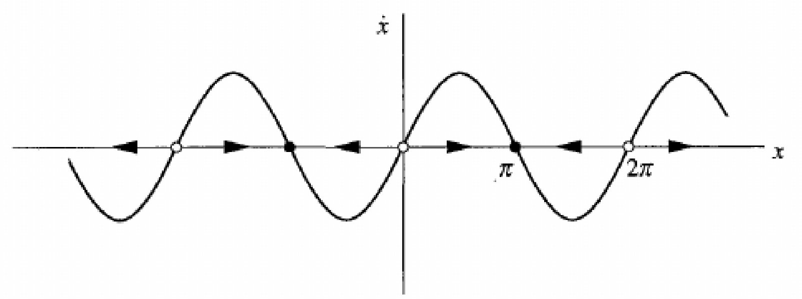


Figure 3.2: Phase flow and fixed poitns of the the one dimensional dynamical system $\dot{x} = sin(x)$.

Consider the trajectory of a point starting from a slightly positive state. As in that region $sin(x)$ is positive it will grow. Its growth will not be fast as the value of its derivative will be small around 0. But, while growing, also its flow will grow, meaning that it will grow even faster and faster until a maximum of the growth rate will be reached at $x = \frac{\pi}{2}$. At this point the growth will still be positive, but will start to fade getting slower and slower until the point $x = \pi$ will be reached where the point will stop its evolution.

Figure 3.3 show shows the temporal evolution of the system in dependence of different starting conditions at $t = 0$. Part of the geometrical approach is to imagine how a point moves, changes its state under the influence of the dynamical system's flow. It is to imagine its *trajectory* while time passes.

Another useful example for a dynamical system is the *logistic equation* which is a simplified model for the growth of a population with a specific growth rate r in an environment with a set carrying capacity K:

$$\dot{N} = rN\left(1 - \frac{N}{K}\right) \tag{3.13}$$

As figure 3.4 shows, the flow of the system has two fixed points, $N = 0$ and $N = K$, the first unstable and the second stable. That means that the system always tends to the carrying capacity of the environment. When $N > \frac{K}{2}$ the growth starts to fade and slowly approaches the point K. Figure 3.5 show the temporal evolution for N for some different starting conditions.

A general formulation for a second order *linear* dynamical system is:

$$\begin{aligned} \dot{x} &= ax + by \\ \dot{y} &= cx + dy \end{aligned} \tag{3.14}$$

or, in a more compact form using vector notation:

$$\dot{\vec{x}} = A\vec{x} \tag{3.15}$$

where

$$A = \begin{pmatrix} a & b \\ c & d \end{pmatrix} \, and \, \vec{x} = \begin{pmatrix} x \\ y \end{pmatrix} \tag{3.16}$$

The solutions of equation 3.15 can be visualised as trajectories in the plane (x, y), in this case called *phase plane*. Further, as this system is linear, we know that a fundamental rule applies i.e. if $\vec{x_1}$ and $\vec{x_2}$ are both solutions then also $\vec{x} = c_1\vec{x_1} + c_2\vec{x_2}$ is a solution for any c_1, c_2. Further, due to the linearity of the system there is only one fixed point $\vec{x^*}$ and that point is $\vec{x} = 0$ as there is is always $\dot{\vec{x}} = 0$, the flow is zero.

Differential equations of this form are in mathematics usually solved by setting:

$$\vec{x}(t) = e^{\lambda t}\vec{v} \tag{3.17}$$

with some v vector and growth rate λ to be determined. Substituting the former in equation 3.15 one obtains

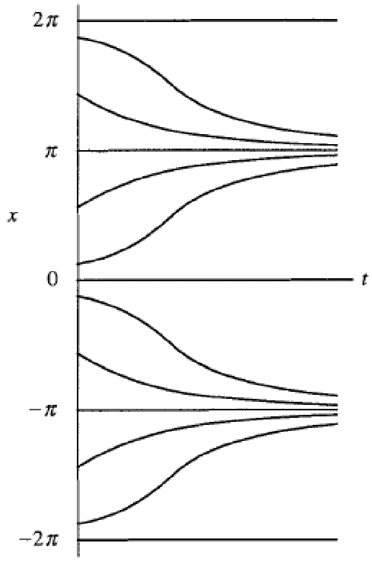


Figure 3.3: Some solutions for different initial conditions to the dynamical system $\dot{x} = sin(x)$.

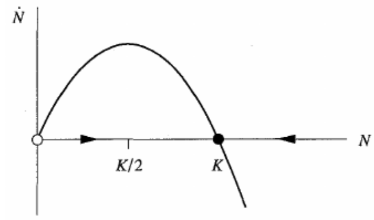


Figure 3.4: Phase flow and fixed points of the *logistic equation*.

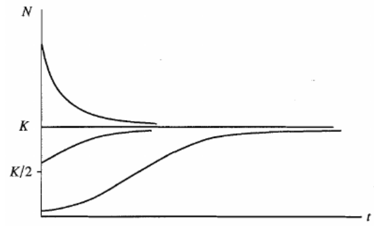


Figure 3.5: Some solutions for different initial conditions to the dynamical system base on the *logistic equation*.

$\lambda e^{\lambda t}\vec{v} = e^{\lambda t}A\vec{v}$ and simplifying the non-zero factor $e^{\lambda t}$ yields:

$$\lambda\vec{v} = A\vec{v} \tag{3.18}$$

which resolves to a "classical" *eigenvalue* and *eigenvector* problem. The above formulation means that we reduce our problem to the easier search for the (in this case 2) directions $\vec{v_1}$ and $\vec{v_2}$ which remain constant under the influence of the dynamical system. This kind of problem pertains to the field of *linear algebra* and is usually solved by solving the *characteristic equation* $det(A-\lambda I)=0$ were I is the identity matrix and det stand for the *determinant* function. Even if here this procedure is explicitly explained only in the case of a two dimensional system, it is valid for general n dimensional linear dynamic systems.

The characteristic equation is thus:

$$det\begin{pmatrix} a-\lambda & b \\ c & d-\lambda \end{pmatrix} \tag{3.19}$$

The determinant gives:

$$\lambda^2-\tau\lambda+\Delta=0 \tag{3.20}$$

where:

$$\begin{aligned} \tau &= a+d \\ \Delta &= ad-bc \end{aligned} \tag{3.21}$$

The above quadratic equation gives two solutions for λ:

$$\begin{aligned} \lambda_1 &= \frac{\tau+\sqrt{\tau^2-4\Delta}}{2} \\ \lambda_2 &= \frac{\tau-\sqrt{\tau^2-4\Delta}}{2} \end{aligned}$$

To each of these two *eigenvalues* correspond two *eigenvectors* $\vec{v_1}$ and $\vec{v_2}$ which can be found by substituting the two solutions back in equation 3.18. One could think of these two vectors as the two main and independent axes along which the flow of the dynamical system unfolds. In particular, given the linearity condition, any initial condition $\mathbf{x}_0$ can be written as a linear combination of these two eigenvectors $\vec{x_0} = c_1\vec{v_1} + c_2\vec{v_2}$ which allows to write the general solution as:

$$\vec{x}(t) = c_1 e^{\lambda_1 t}\vec{v_1} + c_2 e^{\lambda_2 t}\vec{v_2}$$

In dependence of the values of A and thus of τ and Δ the eigenvalues and eigenvector bring forth very different phase flows that produce qualitatively different temporal behaviour. As can be seen from figure 3.6 these can be grouped under six types of classification of the fixed points $\mathbf{x}=0$

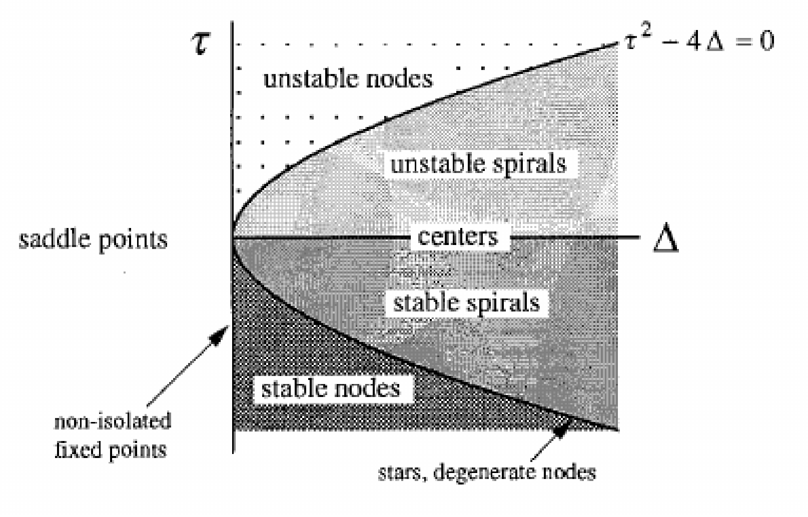


Figure 3.6: Classification of two dimensional fixed point types in dependence on the values of τ and Δ (see equation 3.20). Graphic taken from Steven H. Strogatz *Nonlinear dynamics and chaos: with applications to physics, biology, chemistry, and engineering*. Westview press, 2014

Stable Nodes: In this case both eigenvalues are real and negative e.g. $\lambda_{1,2} < 0$. Meaning that the time evolution, for all points in the phase plane will be governed by an exponential decay toward the fixed point as $e^{\lambda_{1,2}t}$ will tends towards 0 as time advances.

Figure 3.7 depicts the flow generated by the system:

$$A = \begin{pmatrix} -1 & 0 \\ 0 & -1 \end{pmatrix} \tag{3.22}$$

which is also *symmetrical node* or *star*, while figure 3.8 shows that of the system

$$A = \begin{pmatrix} -3 & 0 \\ 0 & -1 \end{pmatrix} \tag{3.23}$$

in which a stronger "drag" is acting along the first dimension. In this case the two eigenvectors correspond with the two plane axes. For the second system the first axis, the "stronger" pulling direction, is also called the *fast eigendirection* and the second *slow eigendirection*.

This kind of fixed point is also an *attracting* node, and in this case in particular it is a *globally attracting* node for all points on the plane. It is further *asymptotically stable*, which means that all trajectories that start near to it will also remain near to it for all times.

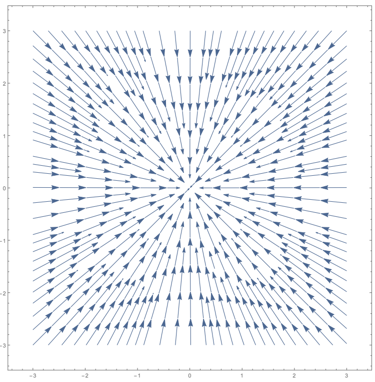


Figure 3.7: Phase flow of a *symmetrical node* or star fixed point.

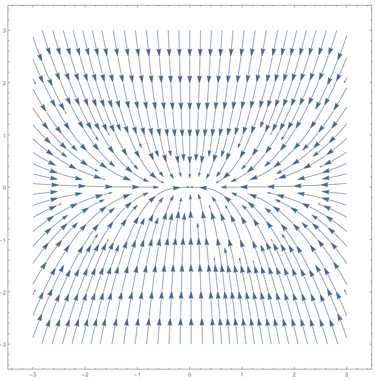


Figure 3.8: Phase flow corresponding to an *asymmetrical node* kind fixed point.

UNSTABLE NODES: In this case both eigenvalues are real and positive $\lambda > 0$. Temporal behaviour corresponds here to an exponential growth starting at any point on the plane and leading away from the fixed point towards infinity as time advances. In figure 3.9 the system:

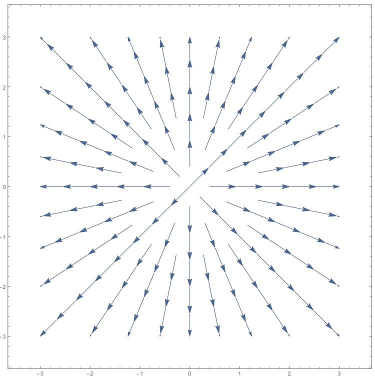


Figure 3.9: Phase flow of a *symmetrical unstable node* fixed point.

$$A = \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix} \tag{3.24}$$

is depicted. In figure 3.10 the system

$$A = \begin{pmatrix} 3 & 0 \\ 0 & 1 \end{pmatrix} \tag{3.25}$$

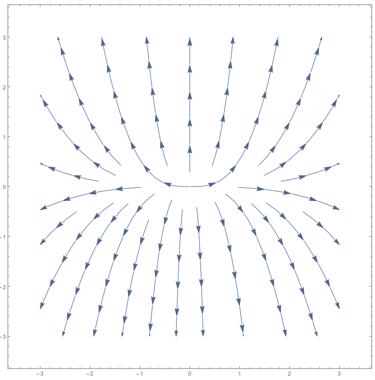


Figure 3.10: Phase flow corresponding to an *asymmetrical unstable node* fixed node.

is depicted. Both are *unstable nodes*.

SADDLES: Eigenvalues are both real, but one is positive and the other negative. Most trajectories grow to infinity away from $\vec{x}^*$ asymptotically along one direction, the eigendirection corresponding to the positive eigenvalue. Only when a trajectory starts exactly on the eigendirection corresponding to the negative eigenvalue, it will move towards the fixed point. The system

$$A = \begin{pmatrix} 1 & 0 \\ 0 & -1 \end{pmatrix} \tag{3.26}$$

is depicted in figure 3.11. The positive growth direction is here the along the x axis and the negative growth direction along the y axis.

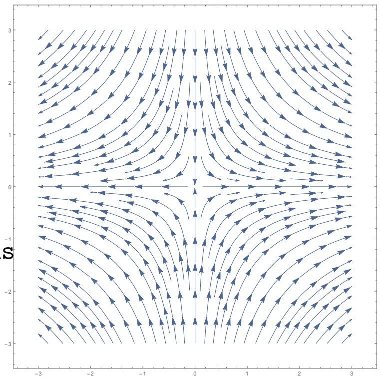


Figure 3.11: *Saddle* fixed point: symmetric flow with stable manifold along the y axis.

$$A = \begin{pmatrix} 0 & 1 \\ 1 & 0 \end{pmatrix} \tag{3.27}$$

This second system's phase flow is depicted in figure 3.12. This is also a saddle fixed point, but the eigendirections are in this case rotated by 45 degrees. The negative growth axis is in this case along the $(-1, 1)$ direction: this axis is also called *stable manifold*, it is the set of initial conditions for which $\mathbf{x}(t) \to \mathbf{x}^*$. The direction of positive growth is here $(1, 1)$ and is also called *unstable manifold* of $\mathbf{x}^*$. A typical trajectory in the phase plane approaches the unstable manifold as $t \to \infty$

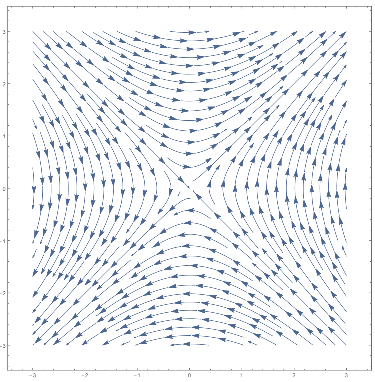


Figure 3.12: *Saddle* fixed point: symmetric flow with stable manifold along the $(1, 1)$ direction.

Centers: The condition $\tau = 0$ results in complex eigenvalues $\lambda_{1,2} = \pm i\,\omega$ and eigenvectors. As the evolution of the system is governed by $e^{\pm i\,\omega\,t}$ The solutions are therefore oscillating, i.e. rotating on closed paths around the centre of the axes. For instance, in figure 3.13 depicts the vector field as generated in the phase plane by the system

$$A = \begin{pmatrix} 0 & 1 \\ -1 & 0 \end{pmatrix} \tag{3.28}$$

and figure 3.14 that of the system

$$A = \begin{pmatrix} 0 & 3 \\ -1 & 0 \end{pmatrix} \tag{3.29}$$

which would be a bit stretched along the x axis.

Centres are regarded as *neutrally stable* as trajectories nearby the fixed point are neither attracted not repelled from it.

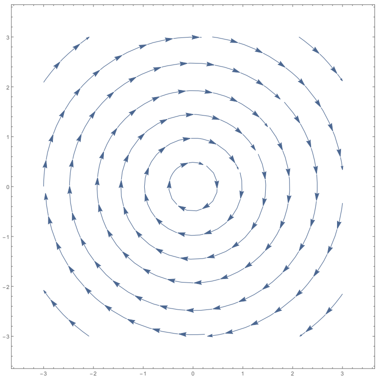


Figure 3.13: Fixed point of *centre* type: symmetric flow.

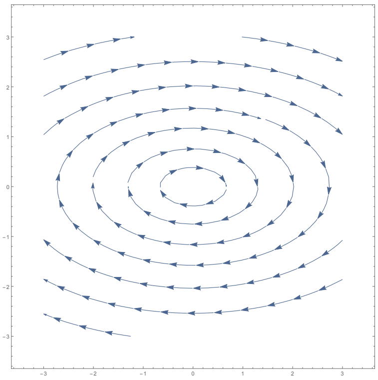


Figure 3.14: Fixed point of *centre* type: asymmetric flow.

Unstable Spirals: The system's eigenvalues can have both a real and a complex part $\lambda = \alpha \pm i\,\omega$. If $\alpha > 0$ the temporal evolution $e^{(\alpha \pm i\,\omega)t}$ is a combination between the oscillatory behaviour of the centre fixed point and of that of the unstable node: oscillations growing away from the fixed point. Figure 3.15 depicts the flow of the system:

$$A = \begin{pmatrix} 0.5 & 1 \\ -1 & 0.5 \end{pmatrix} \tag{3.30}$$

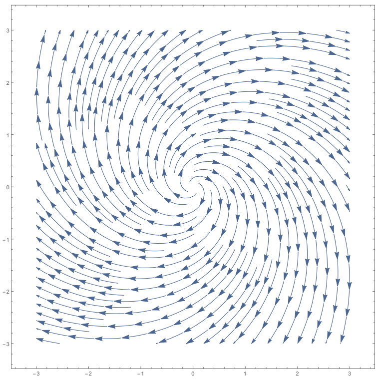


Figure 3.15: Phase flow corresponding to an *unstable spiral* fixed point.

Stable Spirals: If instead the complex matrix eigenvalues have a negative real part $\alpha < 0$ then the temporal evolution of the system will exhibit *decaying oscillations*, slowly decreasing towards the fixed point. This would be the fixed point type corresponding to a damped oscillator. Figure 3.16 shows the flow for the system with matrix:

$$A = \begin{pmatrix} -0.5 & 1 \\ -1 & -0.5 \end{pmatrix} \tag{3.31}$$

These six types of fixed points are fundamental in the study of all dynamical systems and especially in the qualitative analysis of nonlinear systems. In fact, by virtue of the *linearisation* technique, the phase flow of a nonlinear problem can be well approximated by a corresponding linear flow near a fixed point.

The idea is to perform a power expansion of the flow function near a fixed point $\mathbf{x}^*$. That means that for the system:

$$\begin{aligned} \dot{x} &= f(x, y) && (3.32) \\ \dot{y} &= g(x, y) && (3.33) \end{aligned}$$

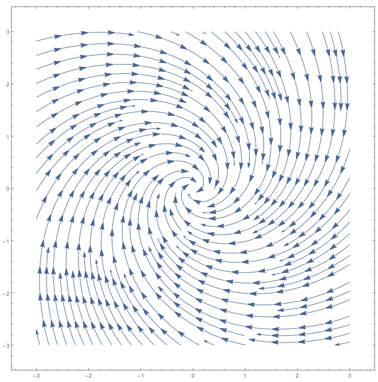


Figure 3.16: Phase flow corresponding to a *stable spiral* fixed point.

near the fixed point (x^*, y^*) could be approximated by:

$$\begin{aligned} \dot{x} &= f(x^*, y^*) + (x - x^*)\frac{\partial f}{\partial x} + (y - y^*)\frac{\partial f}{\partial y} + O(x^2, y^2, xy) \\ \dot{y} &= g(x^*, y^*) + (x - x^*)\frac{\partial g}{\partial x} + (y - y^*)\frac{\partial g}{\partial y} + O(x^2, y^2, xy) \end{aligned}$$

where the partial derivatives are computed at the fixed point and $O(x^2, y^2, xy)$ is shorthand for second order terms in x and y which are very small and therefore negligible. Hence, in matrix form, the flow near the fixed point can be formulated in linearised form:

$$\begin{pmatrix} \dot{x} \\ \dot{y} \end{pmatrix} = \begin{pmatrix} \frac{\partial f}{\partial x} & \frac{\partial f}{\partial y} \\ \frac{\partial g}{\partial x} & \frac{\partial g}{\partial y} \end{pmatrix} \begin{pmatrix} x \\ y \end{pmatrix} \tag{3.34}$$

with the matrix

$$A = \begin{pmatrix} \frac{\partial f}{\partial x} & \frac{\partial f}{\partial y} \\ \frac{\partial g}{\partial x} & \frac{\partial g}{\partial y} \end{pmatrix} \tag{3.35}$$

is called the *Jacobian matrix* evaluated at the fixed point. The Jacobian matrix is the multivariable analog of the usual one-dimensional derivative.

As an example, the following nonlinear system:

$$\begin{aligned} \dot{x} &= -x + x^3 \\ \dot{y} &= -2y \end{aligned}$$

has three fixed points at $y = 0$ and $x = 0$ or $x = \pm 1$. The Jacobian of the flow is:

$$A = \begin{pmatrix} -1 + 3x^2 & 0 \\ 0 & -2 \end{pmatrix}$$

which at fixed point $(0, 0)$ becomes

$$A = \begin{pmatrix} -1 & 0 \\ 0 & -2 \end{pmatrix}$$

Which is the fixed point of a stable node, with fast eigendirection along x. While at the fixed point $(\pm 1, 0)$ the Jacobian is:

$$A = \begin{pmatrix} 2 & 0 \\ 0 & -2 \end{pmatrix}$$

which is the fixed point of a saddle with stable manifold on the y axis. That is, with this technique we can qualitatively look at the nonlinear system as a sort of "combination" of multiple linear system around its fixed points.

However, not all of the basic fixed points have the same *structural stability*, which means that for some fixed points an arbitrary small perturbation changes the stability of the fixed point. For instance given a centre an arbitrary small amount of damping would transform it into a spiral, which has a completely different stability

behaviour. Instead, fixed points which already have $Re(\lambda) \neq 0$ for both eigenvalues are called *hyperbolic* and are much more resistant to small perturbations as the centres.
As a consequence, regarding nonlinear systems, if the Jacobian of a fixed point has all eigenvalues with non-zero real part, then the local phase flow near that point is *topological equivalent* to the phase portrait of the linearisation. Topological equivalent means that there exists a homeomorphism (continuous function with continuous inverse) that maps the one into the other.

A special and important variety of fixed points appearing in two dimensional systems is the *limit cycle*, which is a typical nonlinear phenomenon. A limit cycle is an *isolated* closed trajectory in phase space. While in the *centre* fixed point type all trajectories are closed on themselves, in this case there is only one closed curve cure in the plane. All other trajectories on the plane either spiral away or towards this closed curve. If all neighbouring trajectories spiral towards it, that would be a *stable limit cycle*, while if trajectories would spiral away from it we would observe an *unstable limit cycle*. The system:

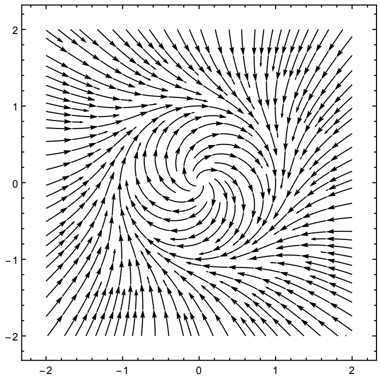


Figure 3.17: Phase flow of the *stable limit cycle* attractor.

$$\begin{aligned}\dot{x} &= y + x(1 - x^2 - y^2) \\ \dot{y} &= x + y(1 - x^2 - y^2)\end{aligned}$$

will produce the phase flow and phase trajectories as depicted in figures 3.17 and 3.18; the fixed point $\vec{x}^* = (0,0)$ is therefore a stable limit cycle. While the system:

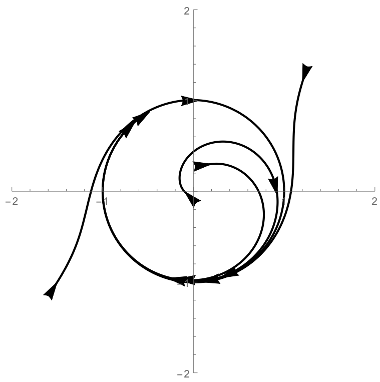


Figure 3.18: Some *phase trajectories* produced by *stable limit cycle* attractor.

$$\begin{aligned}\dot{x} &= y - x(1 - x^2 - y^2) \\ \dot{y} &= x - y(1 - x^2 - y^2)\end{aligned}$$

would instead result in a phase flow which pushes all trajectories (except the one lying exactly on the limit cycle's manifold) away from it, on one side spiralling down towards the centre, on the other towards infinity (see figure 3.19).

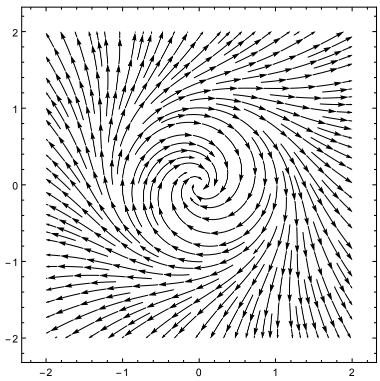


Figure 3.19: Phase flow of the *unstable limit cycle* attractor

Another important aspect to note is that in the limit cycle case the amplitude (and frequency of course) of the oscillatory behaviour is determined by the system itself, from within it. While in the case of centre fixed points the amplitude of the oscillations is determined by the initial conditions and a slight perturbation will therefore have an effect which lasts forever. The limit cycle is therefore sturdier with respect to internal influences and is thus structurally more stable. In the case of the stable limit cycle, after a short time of adaptation to the perturbation, the system will return to its "favourite" oscillation frequency and amplitude.

Limit cycles are of particular scientific interest as they model system which exhibit self-sustained and activated oscillations even in absence of external driving forces. This type of systems are very common in nature and biology e.g. the beating of the heart, the sleep/wake cycles etc.

For systems of three dimensions, all the type of fixed points we have found in the two dimensional cases and of course the limit cycles could appear. In many cases, the temporal behaviour one can encounter in dynamical system with this dimensionality can be qualitatively analysed in terms of combinations of the fixed point types we have already encountered in the two dimensional cases: for instance there can be flows in phase space which are the result of a centre fixed point on one plane and of a stable one-dimensional node on the remaining third dimension. Or of a saddle node on one plane and an unstable one-dimensional on the remaining axe. The technique of linearisation can be applied also in this case, therefore complex and nonlinear systems may also be analysed in terms of the behaviour they exhibit near their fixed points.

But in three dimensions a very special behaviour type can appear, which is not possible in lower dimensions. It's the *chaotic behaviour*. Glimpses of the possibilities of a chaotic behaviour could already be found in Poincaré's work, but it is only in the 1970s that the groundbreaking work of Lorenz[5] has been acknowledged and began to be a central (if not *the* central) topic in dynamical systems theory. Studying meteorological phenomena and trying to model them mathematically, Lorenz discovered a dynamical system that was *inherently unpredictable*, which does not mean that the system evolves "casually" without a rule or randomly. It means that its dependence on the initial conditions (i.e. the starting point in the phase space for a trajectory) is extremely strong. More precisely: Consider two points in the three dimensional phase space of this system which are arbitrarily near to each other and let them be the starting point of a trajectory in phase space i.e. they evolve according to the system's formulation. What will happen is that the two trajectories starting from the two points after some time will be very far from each other, eventually following completely different paths. This is a qualitatively different kind of behaviour than all we have see until now. In two dimensions, two points near to each other will bring forth trajectories will will *stay* near to each other. The consequence of chaotic behaviour is that, as it is not possible to determine the initial condition of any system with infinite precision,

[5] Edward N Lorenz. Deterministic nonperiodic flow. *Journal of the atmospheric sciences*, 20(2): 130-141, 1963

and only rough approximations are possible, these kind of systems are inherently *unpredictable*. In terms of differential equations, Lorenz's dynamical system is formulated as:

$$\begin{aligned}\dot{x} &= \sigma(y-x)\\ \dot{y} &= x(\rho-z)-y\\ \dot{z} &= xy-\beta z\end{aligned}$$

where σ, β, ρ are fixed parameters.

But Lorenz discovered more. He has observed that, despite the inherent impossibility to know the exact state of the system at some time, there was some kind of *structure* in how different trajectories in phase space would evolve (see figure 3.20). The trajectories seemed to revolve and oscillate around a *strange attractor* which he called and "infinite complex of surfaces". Today, we would say *fractal* for describing this special kind of spatial structures.

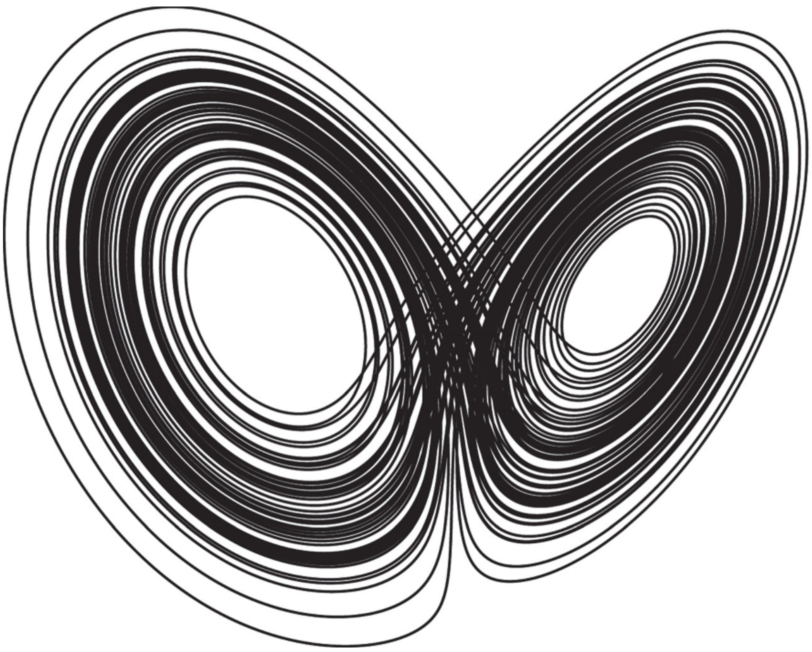


Figure 3.20: A phase space trajectory produced by the three-dimensional Lorenz system

A full treatment of this topic is of course not possible in such sort introduction. Still, the important aspect to underline is that these kinds of systems approach even more the behaviour of everyday life: structures of growing plants, the weather etc.: phenomena which generate structures that are self-similar but at the same time always changing. Even more essential is that the dynamical systems theory provides relatively compact descriptions and a powerful visual language through which *formulate* and *analyse* those phenomena.

As most of nonlinear dynamical systems, chaotic systems are not solvable. As I said before, this means it is not possible to reach a mathematical formulation, an equation which would directly describe the system state's evolution in time. That is, the behaviour of the systems remains implicit in the differential equations that describe it and cannot be "unpacked" into a function $\mathbf{x}(t)$. But how then is it even possible to study those systems? How can a phase trajectory for the Lorenz system as in figure 3.20 be drawn? One of the possible methods for the analysis of chaotic systems is *numerical simulation*. The idea is that as the systems are not solvable, but yet provide definite rules of evolution in time, in order to be able to observe how this evolution behaves i.e. which kind of trajectories it produces, the only possible way it to actually follow the evolution of one point of the phase space under the system's flow. Meaning to actually "sit" on this chosen point, compute the flow at that point and make a small step into that direction, then recompute the flow at that point and make the next step. Re-iterating this process means to *simulate* the system, to perform a *numerical integration*[6] of it and results in a trace showing the system's temporal behaviour in dependence of its initial condition. The implementation and execution of simulations on computers has grown into one of the most used methods in the study of dynamical systems, practically giving birth to a novel method for research in physics and mathematics, the so-called "third way" between the empirical and the theoretical praxis.

[6] Refer to the section *rattle* integration algorithms in the Appendix for an introduction to the problem of numerical integration.

3.2 Dynamical System and Cognitive Science

The enactive theory's understanding of cognition based on a sensory-motor coupling of the living agent with its environment, as an ongoing interaction, a process not based on static images or representations, resonates well with a dynamical systems view. And in fact, enactive theory, strongly refers to dynamical systems in describing its perspective on cognition.[7]

[7] Evan Thompson. *Mind in life: Biology, phenomenology, and the sciences of mind*. Harvard University Press, 2010; and Evan Thompson and Francisco J. Varela. Radical embodiment: neural dynamics and consciousness. *Trends in Cognitive Sciences*, 5(10):418-425, October 2001

In particular, enactive theories rely on a specific approach followed in cognitive science which describes cognitive systems as dynamical systems. According to this perspective all aspects of action, perception and cognition should be tackled from a dynamical perspective. Aspects of the internal structure of agents, as the coupling between sensory and motor systems as well as the interaction between perception and higher cognitive processes and, naturally, the mutual influence of agent and environment should be formulated in terms of dynamical systems. That is, systems in which these "elements" are bound in a continuous interaction which is *defining*: they cannot be considered in isolation and together they form one system of intertwined parts.

This approach contrasts with (current) proponents of so-called cognitivist or computationalist hypotheses which define artificial or natural cognitive agents in terms of computational "machines", that is in terms of symbol-processing. This opposition is best explained in the words of philosopher Timothy van Gelder, one of the strongest proponents of this theory:[8]

> *The cognitive system is not a computer, it is a dynamical system. It is not the brain, inner and encapsulated; rather, it is the whole system comprised of nervous system, body, and environment. The cognitive system is not a discrete sequential manipulator of static representational structures; rather, it is a structure of mutually and simultaneously influencing change. Its processes do not take place in the arbitrary, discrete time of computer steps; rather, they unfold in the real time of ongoing change in the environment, the body, and the nervous system. The cognitive system does not interact with other aspects of the world by passing messages or commands; rather, it continuously co-evolves with them.*

An essential and characterising aspect of the dynamical approach is how it sees cognition fundamentally as a temporal phenomenon, as being *in* time. Time is at the heart of the dynamical perspective: that means the focus is how the system evolves in time, rather then on its *state*, on the temporal unfolding of its behaviour. The beginning and end of the cognitive process is secondary, maybe not interesting at all: cognition is *ongoing*.[9]

Picking up on this perspective, Randall Beer attempts to formulate a simple model for agent-environment interaction in terms of a dynamical system.[10] He poses that both the agent A and environment E are dynamical systems: their states would then evolve by $\dot{\mathrm{x}}_A = A(\mathrm{x}_A;\mathrm{u}_A)$ and $\dot{\mathrm{x}}_E = A(\mathrm{x}_E;\mathrm{u}_E)$. $\mathrm{x}_{A,E}$ represent their internal state and $\mathrm{u}_{A,E}$ stand for parameters that are time-independent internal to the systems. A further assumption is that both systems posses convergent dynamics: i.e. they "tend" to maintain their states in a bounded region and not diverge into infinity. Now, agent and environment system are in constant interaction, which means that some of their parameters are dependent on each other's state through a coupling function. This function will be S for the sensory function coupling environment state and agent's parameters and M for the motor function connecting the agent's state with the environment's. Thus the coupled system could be rewritten

[8] Robert F Port and Timothy Van Gelder. *Mind as motion: Explorations in the dynamics of cognition.* MIT press, 1995

[9] Evan Thompson. *Mind in life: Biology, phenomenology, and the sciences of mind.* Harvard University Press, 2010; Tim Van Gelder. The dynamical hypothesis in cognitive science. *Behavioral and brain sciences*, 21(5):615-628, 1998; and Esther Thelen. Time-scale dynamics and the development of an embodied cognition. In Robert F. Port and Timothy van Gelder, editors, *Mind As Motion - Explorations in the Dynamics of Cognition*, chapter 3, pages 69-100. MIT Press, 1995

[10] Randall D Beer. A dynamical systems perspective on agent-environment interaction. *Artificial intelligence*, 72(1-2): 173-215, 1995

as (see figure 3.21):

$$\dot{x}_A = A(x_A; S(x_E); u'_A)$$
$$\dot{x}_E = E(x_E; S(x_A); u'_E)$$

Where the $u'_{A,E}$ stand for all parameters that are excluded from the coupling. This emphasises the role of *feedback* in the system. Every action M of the agent modifies the environment's state which in turn affects the agent through the sensory connection S. So, both systems are continuously affecting each other's phase flow. As not all parameters are under the influence of the other system, each element in this situation cannot specify the future trajectory of the other; rather it acts like a *perturbation* on the other's dynamics and trajectory. Beer underlines how agent and environment have to be considered as a whole system whose properties do not reside in either of the two interacting components. Further, the agent's behaviour is not located just in itself or the environment alone, but in the coupled system; the agent's behaviour is determined by its internal dynamics and its interactions with the environment, it *emerges* in the interaction process.

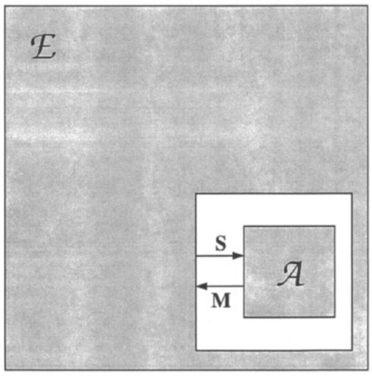


Figure 3.21: An agent and its environment as coupled dynamical systems. From: Randall D Beer. A dynamical systems perspective on agent-environment interaction. *Artificial intelligence*, 72(1-2): 173-215, 1995

Emergence is a term that appears throughout the literature in conjunction with the dynamical approach. The term indicates a coherent perceptible process which arises from the interactions between the parts of the system. It is a higher order organisation of the whole system into a recognisable structure which arises from the low level interaction. That is, it is a behaviour of the system which is not pre-specified or formulated in the rules of interaction, but surfaces as a consequence of those: most importantly, it is an *unpredictable* phenomenon which materialises spontaneously and surprisingly. Enaction theory in particular stresses that *emergence* has a two-way quality: it does not only indicate that a whole arises for the organisation of the parts, but also that the parts arise from the whole. The particular behaviour of each part of the whole is determined by the whole as much as the whole is determined by the interacting parts. This *dynamic co-emergence*, returning to Randall's system, means exactly that the properties of the joint system environment-agent are emergent from their interaction but at the same time co-determine their behaviour.

3.3 Dynamical systems in Electronic and Computer Music

Dynamical systems enter the praxis of electronic and computer music in various ways, but mostly as models implemented and simulated on a digital computer. The evolving state of a system, as it results from the numerical integration of its rules, is the material used musically. The interest of composers was in particular captured by the complex paths chaotic phenomena could generate and by the possibility to produce a wide range of diverse temporal behaviour modifying very few parameters of a model.[11]

A first approach uses dynamical systems mostly in the form of iterated maps: a different formalism of dynamical systems in which time is taken to be discrete and not continuous as in the theoretical introduction at the beginning of this chapter. In particular, these systems have been used in order to produce traditionally notated scores and can therefore be categorised under the praxis of algorithmic composition.[12] In these cases dynamical systems, mostly chaotic, have been in a way *instrumentalised*, used as tools aiming at generating temporal structures which present a high level of complexity and yet a sort of coherence deriving from the simple rules they employ. The fascination for composers for this use of dynamical system leads back to the belief that a whole world of possible temporal processes lie at their disposition just by slightly turning some parameters of the system.

Chaotic dynamical systems are also used in sound synthesis: in this case their evolution is more or less directly "audified" and translated into sound. Those systems can be realised through analog circuitry or digital computation.[13] The encounter with the particular system's behaviour is in this case unmediated by the step of transposition into a traditional musical notation. Of course, there are some steps involved in the process that transforms the state of the system into sound, but still the directness of the situation of listening in *real-time*, that is while the system is actually evolving, to the sound it produces, allows for an essentially different experience than in the previous algorithmic approach. The most salient qualities of the sonic output being the wide range of timbral qualities that can be produced and the low dimensionality of the parameter space in contrast to the space of diverse temporal and sonic behaviour that can be produced.

Given the unpredictability of these systems' behaviour and their extreme sensitivity on initial conditions, this situation affords a particular explorative attitude. In order to build a perceptual "image" of the system's behaviour a deeper engagement from the side of the musician/composer is needed. By employing interfaces through which parameters of the running model can be modified, or eliciting the system's responses with some external perturbing input,

[11] Strictly speaking physical modelling synthesis techniques are also part of this category as physical models are a subset of dynamical systems, but I will not refer to these methods here as I am more interested in approaches that receive the peculiarities of an approach based on dynamical systems

[12] Michael Gogins. Iterated functions systems music. *Computer Music Journal*, 15(1):40-48, 1991; and Jeff Pressing. Nonlinear maps as generators of musical design. *Computer Music Journal*, 12(2):35-46, 1988

[13] Dan Slater. Chaotic sound synthesis. *Computer Music Journal*, 22(2):12-19, 1998; and Agostino Di Scipio. Iterated nonlinear functions as a sound-generating engine. *Leonardo*, 34(3):249-254, 2001

it is also possible to act on the system during its evolution. A different type of contact could therefore be established which extends into live performance situations.[14]

The use of dynamical systems affords a fundamentally different process than usually in the development of sound synthesis methods. Typically, the sonic result is pre-specified and the sound synthesis engine is implemented and adapted towards the achievement of that result. In the case of chaotic dynamical systems synthesis instead, the model that produces the sound is specified by the composer through its rules of evolution, but the sonic result is unknown a priori. An actual exploration of the behaviour space this process generates is necessary in order to actually construct the piece. I see here a connection to the concept of *non-standard synthesis* as depicted by Luc Döbereiner.[15] Sound synthesis through dynamical systems essentially consists of the formulation of rules of evolution or coupling. Sound is not specified by its perceptual appearance, but by the process that constructs it. This process becomes the object of composition. Of a composition that extends into sound synthesis, not in the sense of a composition *with* sound, but as composition *of* sound in terms of processes. A process whose result is largely unknown at its onset and that has to be actually carried out, especially if it includes external disturbances.

Further, temporal scales in which the system's evolution takes place are joined in a continuum: e.g. oscillations can range from the audible domain to periods of seconds or hours in dependence of its parameters while the formal system itself remains unaltered. Dynamical systems offer a formulation framework in which all temporal aspects of sound and its organisation could be integrated. Or, from a more deeply dynamical perspective as proposed by Di Scipio, conceives of all temporal aspects of such a generative composition, microscopic to macroscopic as emergent from low-level nonlinear interactions.[16]

The works and thought of Agostino Di Scipio are paradigmatic for a *thinking in terms of* dynamical systems in computer music. His work is central for this dissertation and a great inspiration for my artistic work. Di Scipio starts by observing that, in common computer music practice, an "interactive" musical system actually implies a linear relationship between performer and system:[17] "agent acts, computer re-acts". The problem he sees is that "the sound-generating system is not itself able to directly cause any change or adjustment in the external conditions set to its own process", that is, it has no part in the determination of its own state and has to completely rely on the dynamics of the performer. His proposition is to

[14] Tom Mudd, Simon Holland, Paul Mulholland, and Nick Dalton. Dynamical interactions with electronic instruments. In *Proceedings of the International Conference on New Interfaces for Musical Expression*, pages 126-129. Goldsmiths, University of London, 2014

[15] Luc Döbereiner. Models of constructed sound: Nonstandard synthesis as an aesthetic perspective. *Computer Music Journal*, 35(3):28-39, 2011

[16] Agostino Di Scipio. Iterated nonlinear functions as a sound-generating engine. *Leonardo*, 34(3):249-254, 2001

[17] Agostino Di Scipio. 'Sound is the interface': from interactive to ecosystemic signal processing. *Organised Sound*, 8(3):269-277, 2003

conceive interaction as a "by-product of lower-level interdependencies among system components": that is, interaction is what happens when entities (or agents) are bound in an interdependent relationship. This perspective strongly refers to the enactive approach in Varela, Maturana and Thompson's work. In particular, Di Scipio sees the computer music system as a dynamical system that has both the faculty to sense external changes in the environment it is embedded in and to self-observe its own state thus becoming a self-organising system: a perspective that resembles the definition of agent I have elaborated in the previous chapter (see 2.4 Enaction). In Di Scipio's work, performer, computer system and environment form together a system in which interaction is constituent. The interactions happening in the system would be the result of planned interdependencies among the system's components: this is the region in which composition would actually take place. In Di Scipio's words, referring to Chadabe's *interactive composing*:

> *This is a substantial move from interactive music composing to composing musical interactions, and perhaps more precisely it should be described as a shift from creating wanted sounds via interactive means, towards creating wanted interactions having audible traces. In the latter case, one designs, implements and maintains a network of connected components whose emergent behaviour in sound one calls music.*

He understands his pieces and his sound installations as components of an *ecosystem*, in which audience, performers, machines, but also the room acoustics have a structural i.e. constituent role. An ecological perspective on musical performance considers all elements, which traditionally may be considered as disturbances or sources of error or unwanted deviation in performance, as an even essential component of the musical outcome.[18] Thus he directly addresses those elements in his pieces and makes them part of a complex network of composed interrelations. The tool he uses in this endeavour are *feedback systems*: computer systems which construct a closed loop between sonic input captured by a microphone and their sonic output projected by the loudspeakers: a computational mechanism which has only sound as interface and is "immersed" in the physical world "constantly affecting the sonic ambience in that environment and constantly being affected by it".[19] The aim is to realise a complete dependency between computer music system and the ecosystem it is in:

[18] Jonathan Impett. Interaction, simulation and invention: a model for interactive music. In *Proceedings of ALMMA 2001 Workshop on Artificial Models for Musical Applications*, pages 108-119, Cosenza, Italy, 2001; and Simon Waters. Performance ecosystems: Ecological approaches to musical interaction. *EMS: Electroacoustic Music Studies Network*, pages 1-20, 2007

[19] Agostino Di Scipio. Listening to yourself through the otherself: on background noise study and other works. *Organised Sound*, 16(2):97-108, 2011

> *There is no way to isolate the system input from its own output, as all output is an input. The very idea of an input/output system should be abandoned, in this context. The room space becomes the medium through which the process hears itself and acts upon itself.*

These pieces, the computer system they employ, do not exist without performance, they need the contingencies of a real performance in order to function: "there is no form without performance".

Emergence is a concept that is central in Di Scipio's work: he refers here to the definition of the phenomenon given in the context of enaction theory as upward and downwards-causation[20]. But apart from these definitions, what I believe is meant here by emergence, is the appearing of the *unexpected* and *unpredictable*. That is, moments in which the mutual interaction of the entities in a sonic ecosystem appear to *self-organise* and bring forth a global behaviour otherwise impossible to produce, as it is impossible to solve the nonlinear dynamical system they produce. In this sense, composing in terms of dynamical systems means to compose interdependencies such that emergent phenomena occur. It means to create the conditions for being surprised, for experiencing the unexpected.

[20] Evan Thompson. *Mind in life: Biology, phenomenology, and the sciences of mind.* Harvard University Press, 2010

However, longing for the unexpected means also to expose to *failure*. Creating such a tight feedback coupling between computer system and its environment (or performer) actually aims at producing a completely circular situation. None of the components is in actual control of the situation and neither they can be, without disrupting interaction. That means there is no way to predetermine that errors will not happen, therefore failure and the way to cope with it should be made part of the composition. Di Scipio addresses this issue in his scores when he describes the "emergency measures" to take in case of failure in order to push the system towards more stable regions of behaviour.[21]

[21] Julia H Schröder. Emergence and emergency: Theoretical and practical considerations in agostino di scipio's works. *Contemporary Music Review*, 33(1): 31-45, 2014

I believe that Di Scipio's work truly captures some of the most fundamental qualities of interaction I want to address. In particular that, in his understanding, interaction cannot be relegated to an ancillary function, it needs to be at the centre of compositional practice thus becoming a form-giving or even a generative principle. In his words:[22]

[22] Agostino Di Scipio. Iterated nonlinear functions as a sound-generating engine. *Leonardo*, 34(3):249-254, 2001

> *Understanding interaction as the object of composition means that the internal ecology of the musical process is captured in the mutual, causal interconnection of many component elements: changes in the ambience*

> *response [...] determine unpredictable but consistent reactions and adaptations in the machine's behavior [...], which in turn causes unpredictable but consistent reactions and adaptations in the ambience and the visitors' behaviour.*

I believe that dynamical systems provide an apt framework not only as metaphor in describing interaction in this sense, but also in realising actual computational artefacts (I avoid calling them computer music instruments) materialising such interactive systems.

3.4 A sense for change: behaviour

For Alva Noe and O'Regan "to perceive is to exercise one's skilful mastery of the ways sensory stimulation varies as a result of bodily movement".[23] Thus, our perceptions base on differences that our sensory-motor system detects. That is, when our senses "detect" something, a difference is formed with respect to the motor system. Also, as Noë explains, our visual perception is strongly dependent on the continuous movements our heads and eyes perform, which result in different visual images detected by our retina: the difference those images contain are then reintegrated into the image we perceive. That is, our sensory-motor system even *produces* differences in order to be able to perceive. This is particularly evident in the case of visual perception, but there is evidence that similar mechanisms can be found also for other senses.[24]

I draw a connection here to the properties of the sensual receptors as described by neuroscientist Alain Berthoz:[25]

> *Sensory receptor functions have a predictive quality. Receptors can detect the derivatives (that is, velocity, acceleration, changes in force and pressure) of the physical variable that stimulate them. Detecting changes in a variable allows the receptors to predict the value of that variable at a future time.*

I gather therefore that our whole perceptual system is very well trained to capture differences, especially time differences, i.e. derivatives. Then when we perceive we tend to "solve" these embodied differential equations, of course not in a mathematical formulation, but in the sense of a predictive tension towards an anticipated temporal state. I believe that Edmund Husserl would call this tension *protention* in terms of his phenomenology of time. As Merleau-Ponty explains:[26,27]

> *Husserl uses the terms protentions and retentions for the intentionalities which anchor me to an environment.*

[23] J Kevin O'Regan and Alva Noë. A sensorimotor account of vision and visual consciousness. *Behavioral and brain sciences*, 24 (5):939-973, 2001

[24] Alva Noë. *Action in Perception.* The MIT Press, 2004

[25] Alain Berthoz. *The brain's sense of movement.* Harvard University Press, 2000

[26] Maurice Merleau-Ponty. *Phenomenology of Perception.* Routledge, 2002

[27] In the English version the french term *protention* is erroneously translated with *protection*. Here, I will use the term *protention* instead.

> *They do not run from a central I, but from my perceptual field itself, so to speak, which draws along in its wake its own horizon of retentions, and bites into the future with its protentions. I do not pass through a series of instances of now, the images of which I preserve and which, placed end to end, make a line. [...]. Time is not a line, but a network of intentionalities.*

That is, the very perception of time is based on a continuously performed "movement" that starts somewhere in the set of retentions, the just passed past moments, but still retained in our consciousness as a sort of lingering echo, passes through the present and protends into an anticipation of the future. Perceiving time means therefore continuously re-constructing the coherency that unites moments and projecting it before us, into the future.

In my words, this means that we are sensible to dynamical systems. In particular, we are *trained* to see and interpret the world in terms of dynamical systems, as a system or a collection of systems that produce temporal variations on the base of some rule, of a "differential equation". Perceiving or feeling this equation gives us the possibility to look in the future. Of course, this seems obvious as the physical world we are immersed in is an aggregate of dynamical (physical) systems: not being able to understand these would lead to evolutionary failure. Nonetheless, the interesting consequence here is that using dynamical systems for composing sonic processes would then resonate with the very fundamental mechanisms of perception in eventually making those more perceivable or "graspable". This is one of the assumptions lying behind this work.

4
Case Studies

In this chapter a third path is pursued, this time through a series concrete works: the implementation of software framework for physical and dynamical systems modelling with some experiments realised with it, the research project *Embodied Generative Music* with some of its artistic case studies and the proposal for a thought framework for interactive environments tested in a small experimental setting. I draw a thread through some of the important works and research projects which had an influence on the development of this dissertation. For the sake of clarity the narration I have constructed attempts to make this path appear smooth in how each idea or realisation follows each other. Of course, this is a construction which does not always coincide with the reality: temporal extensions might strongly overlap.

Still, this part is of particular importance as it wants to clarify how in fro this dissertation, artistic practice and experimentation played a central methodological role. Already in the operation of transferring ideas or utopias from a theoretical abstract context into a material artefact (a software but also an artistic piece or a sound installation) many decisions have to be taken and new thoughts appear that reflect back on the starting conditions. Further, practical experimentation, observation and experience of the aesthetic qualities of one's own ideas allows for new formulations and a different kind of understanding. I would say that this self-exposure to my own thoughts in form of aesthetic artefacts was (and is) one of the main methodological tools I have used in the course of this dissertation. This chapter tries to make this clear.

From another perspective, this chapter collects works of very of different "materiality". They are drawn from different contexts, like mathematics, software development, artistic research, computer music research, philosophy and cognition theory, fields that are far apart from each other. The risk therefore is that these materials might appear as too heterogeneous to construct a coherent discourse. This would be probably true if they would be left "dangling" without roots and I hope that the previous chapters provide those groundings. Together with the artistic works collected in the appendix to this text, they form so to say the frame of this chapter.

4.1 The rattle *System*

rattle is the name I gave to the small software library I've been developing in order to formulate and realise experiments and the studies that follow. In this sense for many of those works, *rattle* has been a precondition. Still, it could be thought that the description of a software framework would not fit under in the chapter *Case Studies*; such part would be better suited for an appendix or a decisively more technical section or an "instrumental" context. This is not a mistake, but rather a statement and an acknowledgement. I consider the praxis of programming and of software development as inextricably intertwined with the evolution of thought and of the ideas that actually are pursued in a research project.

That is, I claim that programming praxis and software development posseses a sort of *excess* as Hans-Jorg Rheinberger[1], citing Derrida, ascribes to the *means* by which experiments are conducted, indicating how those contain more and other possibilities than those to which they are actually held to be bound: they transgress the boundaries within which the research appears to be confined. In my view, this is especially true in the context of a research which is strongly driven by artistic aims, where the relation between realisation, formulation and the artefact is extremely tight, all together forming an almost inextricable compound. Coding, programming and the continuous interaction with the formulations of an idea, play an active role, rather then being purely instrumental, in the sharpening and furthering of ideas and, more importantly, of questions.

[1] Hans-Jörg Reinberger. Experimental systems: Historiality, narration, and deconstruction. *Science in Context*, 7(1):65-81, 1994

In its first incarnation, *rattle* is a physical modelling and simulation software framework. The software tries to offer a programming context in which physical systems, that is systems resembling or exemplifying physical interactions between simple objects can be formulated and simulated. It has been implemented in various programming languages: SuperCollider[2], C, Fortran, and a minimal implementation exists in JavaScript. Each reformulation of this same framework in a different programming language has contributed to tightening and streamlining the code: eventually the core of the whole framework can be expressed in very few

[2] http://supercollider.github.io/, accessed 23/05/2017

functions and classes.

In principle *rattle* implements a mass-force physical modelling method and as such it shares some commonalities with existing software: two of the most notable examples of similar frameworks are *pmpd*[3], a library of objects integrated in the *pure data* open source visual programming language or the software *GENESIS*[4] and *CORDIS-ANIMA*[5] developed by the ACROE-ICA. Still, it retains some differences in purpose as well as in the implementation.

[3] Cyrille Henry. Physical modeling for puredata (pmpd) and real time interaction with an audio synthesis. In *Proc. of the Sound and Music Computing Conference*, October 2004

[4] Nicolas Castagné and Claude Cadoz. Genesis: a friendly musician-oriented environment for mass-interaction physical modeling. In *ICMC 2002-International Computer Music Conference*, pages 330-337. MPublishing, 2002

[5] Claude Cadoz, Annie Luciani, and Jean Loup Florens. Cordis-aniama: Modeling and simulation system for sound and image synthesis - the general formalism. *Computer Music Journal*, 17(1):19 - 29, Spring 1993

- Since the original idea was to develop a tool to explore different behaviours emerging from the evolution of physical systems, *rattle* is not limited to modelling and simulating systems governed by elastic forces or vibrating behaviour. Other physical modelling software used in the computer music context, focuses just such systems: this choice is of course quite natural as in the musical context, oscillating phenomena play a central role both if the aim is to synthesise sound imitating acoustic instruments as well as generate control signals for high level control of sound synthesis or formal structure of generative musical processes. As the interest in developing this tool was less the imitation of some specific behaviour, as the oscillatory behaviour, but to explore behaviour and its properties as a perceptual phenomenon. Therefore a wide range of behaviour formulations and implementations where sought, first limited to behaviour as it is specifically appearing in physical systems (systems that model interactions present in the physical world), then in a more broader understanding based on a dynamical systems' perspective (refer here to Phase Space Thinking: an experiment).

- The very first implementation in the *SuperCollider* platform centred on the simulation of simple models of interacting objects in order to use their movement (e.g. the variation of speed of position) as control signal for spatialisation (see appendix A.2 cornerghostaxis#1) or sound synthesis processes (see the spring scenario described in 4.1.2 An example and some considerations). Only the second reformulation of the framework into a C library allowed to run the simulations at audio rate thus allowing to audify or sonify the movements of the simulated particles to directly synthesise sound (e.g. see appendices A.4 Interstices and A.5 Zwischenräume): a possibility that distinguishes *rattle* from other frameworks which focus on generating control signals from the evolution of the systems i.e. low-frequency signals which are mapped to parameters of synthesis processes running in parallel.

- As the interaction with simulated physical systems was one of the central points in developing *rattle*, the possibility to enter the running simulation in real-time even at audio-rate by acting upon single masses in the system by changing their state by controlling their position (e.g. spring scenario) or even changing parameters of the forces acting on each single particle, is a fundamental functionality which is not offered by other software that aims at physical modelling sound synthesis. In general in such frameworks, after an initial phase in which a more or less complex object is "constructed" from simple building blocks, the particles, when the simulation starts the possibilities of interaction are strongly limited: it is not possible to change structural qualities of the model.

- The models which can be realised in *rattle* are three-dimensional, i.e. the positions and movements of the interacting objects take place in a three-dimensional Cartesian space. Other software makes distinctions between one, two or three-dimensional masses and forces, which cannot be mixed, in order to enhance overall performance of the software. Thus, in *rattle* there are no such distinctions as all particle "share" the same space and always can interact with each other.

- *rattle* was from the beginning been an *Open Source* project. In contrast to some of the tools mentioned above, I have always thought of it as a tool which could and might be used by other researchers and artists with the intention to influence their practice as well as eliciting feedback from them, an instrument that stimulates exchange. *rattle* is open, in the sense that its development and in some way its inner construction, corresponds with an attitude of sharing instead of possession, of questioning instead of instumentalisation, of opening instead of control.

  It has been openly shared and used by colleagues I've been working with. But effectively, even if the software (at least in its latest implementation) is publicly hosted on an online open source software development platform[6], I didn't explicitly work on disseminating it widely and it has therefore not reached many other computer music practitioners and still retains many idiosyncrasies due to the fact that until now I was the only developer. This is something I would like to pursue in the future.

[6] https://github.com/davidpirro/rattle, accessed 01/08/2017

Through the points above shimmers how the idea behind *rattle* is less that of a very specialised tool, apt for solving selected problems in a fast way, also providing potential users with a pleasant and easy to use graphical interface. It is a tool, which aims at providing a platform for formulating and simulating generic physical systems, that is as flexible as possible towards unthought problems. The aspiration of generality leads on the one hand to a wider range of possibilities and on the other hand (the downside) greater complexity and a certain degree of "resistance" in the use and possibly worse computational performance. As a result a greater degree of involvement is required from the user who wishes to operate it: *rattle* is, in its current form, a tool that requires the users to "get dirty", mess with code, try, fail and debug. In other words, *rattle* was not conceived as a complete "instrument" or a plugin that presents some ready solutions or effects; rather, I conceive it as an environment that offers possibilities to formulate a particular set of situations that have the potential to bring to light emergent phenomena which could not be foreseen or predicted in advance. *rattle* affords the experiential exploration of these situations.

Due to the generic problems the software tries to address joint with the request that the systems should be at all times accessible to the user or performer to interact in any way, no a priori analysis steps[7] can actually be performed in order to reduce the computational steps needed in real-time. As anything could change during the simulation and nothing can be predicted in advance the simulated systems should remain open to a continuous adaptation to changes. That means that every step in the simulation consists of numerically integrating the equations of motion of the involved particles, the differential equations describing their behaviour in time: this computational step introduces errors that might accumulate very quickly and ultimately drive the simulation into unstable states. Strategies to reduce this effect involve the reduction of the time step used (i.e. more steps are needed to compute the change of state of a system after a time interval) and the increase of the precision of the floating point numbers representation used or the order of numerical integration method used (refer to the section *rattle* integration algorithms for details). All these known recipes involve an increase of computation steps required to calculate each simulation time frame.

[7] For example the *GENESIS* software offers the possibility to run a modal analysis of the constructed object thus pre-computing the spectral structure of its vibrational behaviour: this step greatly reduces the computational power needed in real-time.

These considerations eventually led to the decision to switch from the *SuperCollider* language implementation, to a realisation in the *C* language which could allow to have a more fine-grained control over these aspects and to produce faster code as well. In this implementation, simulations could be run at a much higher rate and thus allowed (as I have noted above) to *directly* synthesise sound. *Directly* here means that positions or velocity values of the particles, i.e. the state of the modelled system, could be immediately used as audio signal, unmediated by control to audio rate conversions, upsampling algorithms or mapping functions which connect the states of the simulation with some synthesis process which runs separately or in parallel. In *rattle* there is no distinction between control and audio rates at all, there are no implicit signal hierarchies: sound synthesis and modelling / simulation have a very tight connection.

Embarking in this programming endeavor meant also to not rely on a series of handy functionalities already implemented in the *SuperCollider* language that had to be re-implemented. On the one hand this meant a great loss of energy and time, but on the other hand, seen in retrospective, that process eventually led to a tightening and a clarification of formulations both in the form of code as well as in the form of thought. It also enabled a better understanding of those functionalities: the need to re-programme those, necessarily led to a better understanding of their workings as well as the side-effects they produce. I would say that this situation eventually gave me the possibility to have a deeper understanding of common computer music algorithms and a better control over my own practice by opening up and re-writing "black boxes", which otherwise would have been used without having a precise understanding of their action.

At last, I would like to point out how this situation of "re-starting from zero", united with my limited programming skills and limited time, led to the condensation of a sort of "method": keep things simple, go to the essential, reduce to the bare minimum, as well as eliminate every algorithm or function that is not fully under control and which could be responsible of unwanted effects. This philosophy infected my way of thinking in many ways and is also reflected in various dimensions of this thesis: from a bird's eye perspective, looking how the whole work evolved, and trying to identify threads running from the beginning to its actual state, I would find that one of the threads is *reduction*, a spirit of removal of non-controlled transformations and a search of the essential qualities of a specific situation (projected as "imagined" or experienced). A method of elimination of unclear concepts or terms, attempting to peel away the layers of interpretation and praxis that might blur the sought "core".

4.1.1 Modelling Paradigms

rattle is based on a *fields* formulation of the forces acting upon particles. In classical mechanics (we will ignore quantum or relativistic mechanics effects), a field is a function that associates a scalar value (i.e. a number) or, in general, a tensor (e.g. a vector) to each point in space: it is a "condition of space"[8]. Temperature, a typical example, is for instance a scalar field $T(x,y,z)$ that associates the temperature value, to each point in space. Instead, the electric field is a vector field which is caused by a charged particle and extends to the whole space. In this case the field function E tells which force F would be experienced by a particle with unit charge at each point in space. So, in general, a particle with charge q in the field E would experience the force:

[8] Richard P Feynman, Robert B Leighton, Matthew Sands, et al. *The Feynman lectures on physics, Vol. 2*. Addison-Wesley, 1964

$$\vec{F} = q\vec{E} \tag{4.1}$$

were the field $\vec{E}$ is is given by Coulomb's law:

$$\vec{E} = \frac{1}{4\pi\epsilon_0}\frac{Q}{r^2}\hat{r} \tag{4.2}$$

where Q is the charge of the particle emanating the field and $\hat{r}$ indicates the unit vector in direction of that particle, the centre of the field.

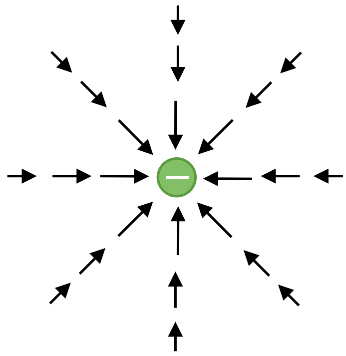


Figure 4.1: The electric field emanating from a negative charge

The electric field is an apt example to illustrate this formalism as also historically *classical field theory* has been developed to formulate the electromagnetic and gravitational fields. In the latter case, the field and the force acting on a mass m would similarly be, by Newton's law of gravitation:

$$\vec{G} = -\frac{GM}{r^2}\hat{r} \tag{4.3}$$
$$\vec{F} = m\vec{G} \tag{4.4}$$

In *rattle* fields are "attached" to a particle, they are a property of particles; they are a method in the particle object in computer programming jargon, the *mass*. Most other particle-based physical modelling frameworks use instead the *links* metaphor for formulating interactions between particles: *links* are in themselves objects which connect two particles at a time. Using fields to formulate those interactions between particles, allows in many cases for a more compact expression of complex interaction relationship networks in a model. Multiple particles might by under the influence of the same field (particle) and there is no need to specify a new *link* object for each of these interactions.

fields in *rattle* are implemented as functions receiving one mass as an argument and returning the acceleration a that mass experiences as a result of being in that field.[9] Each *mass* is equipped with a default *field* function f of the form:

[9] Technically, the *field* function receives two arguments as input, two masses; the first is always the *origin*, the mass that field belongs to (e.g. the centre of the electric field) as is automatically passed by the simulation callback.

$$\vec{a} = \vec{f}(p_0, p_1) = \frac{k_0}{m_1} m_0^{\beta} r^{\alpha} \hat{r} \tag{4.5}$$

where:

- p_0 is the field "origin" particle and p_1 is the particle it is applied to.
- m_1 is the inertial mass of the affected particle and m_0 that of the field's origin particle. Note that m_0 enters the field equation as a parameter with an exponent β in order to account for situations in which the origin's mass is part of the force's formulation (e.g. in the case of gravitational forces, see below): in the default case $\beta = 0$, i.e. the origin's mass has no effect.
- $\hat{r}$ is the unit three dimensional vector that identifies the direction pointing towards particle p_1 from the origin particle p_0
- k_0 can be understood as a general "coupling constant" (or interaction constant), which controls the overall strength of the force particularly in relation to the other fields in the model, e.g. the spring constant in *Hooke's law* (see equation 3.3). This parameter also controls if the force is attractive ($k < 0$) or repulsive ($k > 0$). The default value for $k = 1$.
- α is a parameter controlling the overall behaviour of the interaction force. E.g. with $\alpha = 1$ (the default) the field would model the acceleration caused by a spring. With $\alpha = -2$, $\beta = 1$ and $k_0 = G$ the *gravitational constant*, gravitational forces could be modelled.

The idea of the above formulation for the field is to already provide a default possibility to model most of the fundamental interactions known from classical physics. Still of course this formulation, even if very broad, would not be sufficient to cover all possible physical (and perhaps non-physical) possibilities for defining interaction forces. For instance the field as defined in equation 4.5 could not model the magnetic force field; or, it would not suffice to model the effects of non-linear springs or anisotropic force fields. Therefore, in the spirit of experimentation and openness, *rattle* gives the users the possibility to freely redefine the field function to fit most needs.

rattle also gives the possibility to assign more *fields* to the same *mass* so that it would affect other masses in different ways. This functionality however did not prove to be essential in practice as the possibility to freely define the *field* function actually already provides enough flexibility for formulating the most diverse situations.

Of course, one particle might be under the effect of more fields of multiple *masses*. In that case, the "superposition principle"[10] holds i.e. the effects of the single force fields f_i with $i = 1 \ldots n$ are added up in order to compute the acceleration a for the mass in consideration. Eventually a term accounting for *damping* effects is added into the equation:

[10] Richard Phillips Feynman, Robert B Leighton, and Matthew Sands. *The Feynman lectures on physics. Vol. 1.* Addison-Wesley, 1963

$$\vec{a} = \sum_{i=0}^{n} \vec{f_i} - c\,\vec{v} \tag{4.6}$$

this velocity proportional viscous damping force[11] (c is the so called viscous damping coefficient) may be specified for each *mass* singularly and proves to be an essential variable.

[11] Richard Phillips Feynman, Robert B Leighton, and Matthew Sands. *The Feynman lectures on physics. Vol. 1.* Addison-Wesley, 1963

Many systems might exhibit instability in different ways. This is especially evident when they are interacted with, i.e. a user acts upon a simulated model and therefore changes its state, injecting (or subtracting) energy from the system. The damping force is here a useful (or even necessary) tool to embank those instabilities that would drive the model into an uncontrolled growth.

When all elements of a model are defined and in place, the simulation can be started. The simulation algorithm is a re-iterated process subdivided into two steps:

1. For each mass the acceleration is computed using equation 4.6. By numerical integration using a simplectic implicit Euler (or Verlet) algorithm (see appendix B *rattle* integration algorithms) the displacement and velocity variation vectors for the next frame are computed, but not yet applied as well as the effect of friction subtracted.

2. When the above step is finished for all masses in the system, the displacement and velocity variation vectors are applied to each mass.

These two separate step are necessary to avoid the inconsistencies which would arise if the displacement of one mass would be applied before its effect on another mass could be computed. This would be especially dramatic in the case of two (or more) mutually interacting masses. Typically this would lead to the appearance of chaotic behaviour which is just a result of an accumulated error of the numerical integration routine.

In the *rattle* framework there are three principal elements:

1. *masses*: these are the basic objects of the particle based physical modelling. They contain the state of the particles, their three-dimensional position and velocity vectors. Further, each *mass* stores references, i.e. *pointers*, to the other *masses* in the system it is interacting through forces it exerts or by which it is affected. Each *mass* also stores other values which control the form of the field it emanates (the coefficients k and α and the mass m) as well as the friction force it experiences.

2. *fields*: are a property of each mass. *Fields* are functions which implement the formalism of *classical field theory* followed here, i.e. functions which accept two *masses* as input: one is the origin of the field and one the mass that is affected by the field each mass has its own *field*.

3. *scenes*: a scene is a collection of *masses* interconnected by *fields*. Scenes are containers for subsystems in a model. Transformations (e.g. translation etc.) applied on a scene, are applied to all elements in that scene, that is, *rattle* scenes are a convenience tool which facilitates working with collections of masses. Furthermore, scenes can also contain specialised *fields* that are applied to all contained masses: for example, all masses in a scene might be subject to a gravitational force.

4.1.2 An example and some considerations

To clarify how *rattle* has been employed to develop interactive scenarios, I will introduce the *simple spring mass scenario*: This has been one of the first experiments with physical models we have performed in the context of the *Embodied Generative Music* project (see section 4.2 The *Embodied Generative Music* Project).

In this scenario, as well as in the explorations that followed (e.g. A.2 cornerghostaxis#1 or A.3 Tball) the approach to interaction design can be simply formulated as in figure 4.2: The instantaneous performers' state is captured via a motion capture system: this software streams three-dimensional information of the position and orientation of the whole body or a simple joint or an object hold in a hand, into a running physical simulation. An identity mapping assigns this data to the state (i.e. position and orientation) of one of the elements in the

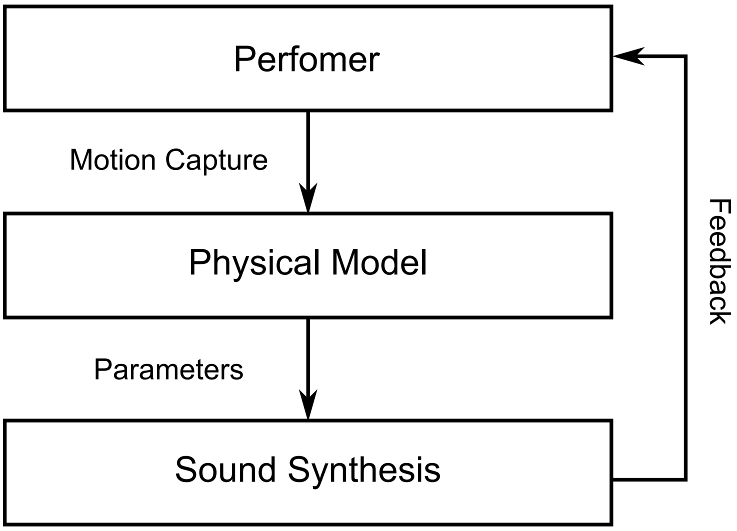


Figure 4.2: A simplified graphical depiction of the apporoach to the design of interaction used in the *simple spring mass scenario*

running simulation. The "virtual" simulation space realises therefore a sort of "double" of the tracked real physical space: the Cartesian axes of the two spaces correspond. Parameters of the sound synthesis process are updated according to the simulated system's state thus producing a variation in its output: this variation can be perceived by the performers giving feedback about the model's internal state evolution as a response to their actions.

In the *simple spring mass scenario* a camera based infrared motion tracking system captures the experimenter's movements used in the physical model (see figure 4.4). More precisely, the tracked position of the hand holding a *rigid body* target is mapped to the coordinates of a particle in a simple model consisting of two masses connected with a spring (see figure 4.4). During the simulation, one of the masses (e.g.the filled black mass in the figure) follows the continuously updated position to the player's hand position (the target he holds), while the other (the black in the figure) is free to move and under to effect of the force the spring exerts.

Thus moving the hand corresponds to a movement of the black mass and causes an elongation of the spring. The white mass would therefore be pulled and would start oscillating around the red one. Of course, as the movements and the model are in three dimensions, continuous and more complex movements of the hand induce more intricate paths. An amount of viscous damping is added to the system so that the oscillation would eventually fade out.

The state of the system is translated into a simple (and crude) sonification by mapping the distance d between the two masses to the frequency of a sine oscillator. It has to be noted that sound is the only feedback offered to the user; there is no access to graphical representation

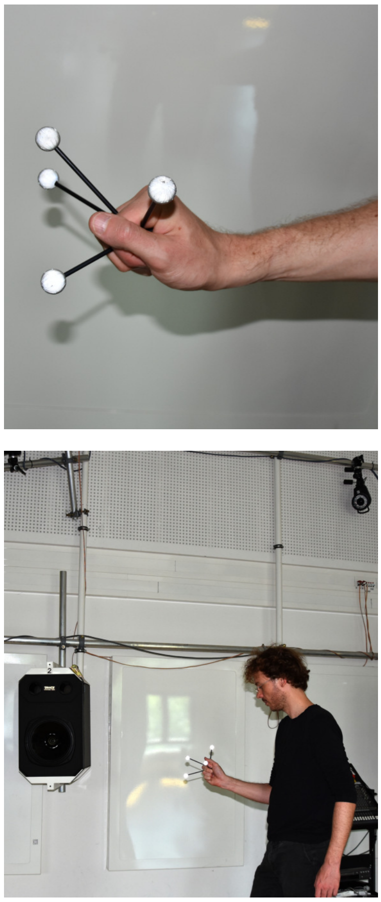


Figure 4.3: The *rigid body* tracking target (top) whose position is reconstructed by an infrared motion capture system by VICON in the CUBE Laboratory at the IEM (bottom, a tracking system camare in the toproght corner).

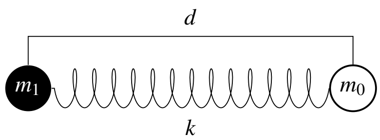


Figure 4.4: Graphical depiction of the *simple spring mass scenario*. The two masses m_0 and m_1 are connected by a spring (harmonic) force with hooke constant k. The movement of the two masses is sonified by mapping the distance d between them to the frequency of a sine oscillator.

of the model's state while interacting with it. This scenario is of course of very limited musical interest, but is reported here as it serves to allows fundamental observations.

Even with such a reduced feedback, users could clearly perceive the state of the simulated system and immediately establish a connection between their actions and the sound. This becomes especially evident when observing how quickly they could attune to the system. Anyone who tested this scenario could readily perceive that it was an oscillatory phenomenon they were confronted with and subsequently find and excite its resonant frequency. That is, after only a few hand movements, it is clear how to move the hand in order to keep the system constantly oscillating at the same pace at the same time performing the smallest possible movements. In its simplicity, the scenario shows how an interactive physical model may elicit an immediate attuning which translates into a *bodily resonance*, a situation where the connection between the perceived cause and effect is almost unmediated.

The role and effect of damping also needs some more attention1. Eliminating this factor from the model, which was the case in a very first test setting, interestingly resulted in a scenario much more difficult to cope and interact with. Each movement of the hand basically resulted in a energy injection into the system which would then oscillate at its resonance frequency forever. Not only in this case the system would almost continuously increase its energy and therefore the oscillations' amplitude, but also the *felt causality connection* between own actions and their effects could not be established stably. Only after introducing the damping term actually the behaviour of the system could be fully grasped and performed with. Even more, as the main characteristic of the interaction in this simple scenario was to play with the resonant behaviour of the system, it could be said that the interaction mainly consisted in exciting the model in such way to exactly counteract damping and therefore remain in a stable energy regime. That is, damping not only seems to be a key factor in allowing to grasp the system behaviour's at all, but also it could be interpreted as the parameter around which the interacting movements of the users revolve, a variable the body can immediately relate to and manipulate.

From a wide perspective, damping, the (more or less) continuous energy loss is a fundamental characteristic of any evolving physical system: frictionless models are a common approximation in physics that are necessary in order to study and understand the basic behaviour of that system. Still, friction or energy loss is a constant force that plays a principal role in the world we are immersed in every day, a "presence" we feel in every action we perform in our reality. It is part of the **resistance** which we are accustomed to experience and identify in any interaction we have with physical systems.

Practice and experience while developing and experimenting with **interactive** physical models as the previous *simple spring mass scenario* has shown that any of those systems, independently of the complexity of the model, seems to need this ingredient in order to be felt as in some way accessible to interaction or resonating with a bodily understanding. This observations lead to basic insights.

A simulated system without any form of structural energy loss would experience a continuous energy injection and therefore continuous growth as a consequence of the modification or excitation caused by interaction. That this situation is clearly perceived as "unrealistic", non-physical or non-bodily, strongly correlates with basic physical laws. This might be an indication of how much physical laws are ingrained in our perception: or of how physical laws embody our experience of the way the world around us reacts to our actions[12].

[12] That is, physical laws formulate what is already known by our bodies. At least what pertains to classical mechanics...

Also, this might be taken as evidence for a perceptual propension to conceive ourselves as part of a system which encompasses that which we are interacting with as well as ourselves. As opposed to being removed from or outside of the system in which we could inject energy at will, we are inclined to perceive ourselves as sharing and operating on the same energy balance our counterpart has access to. After all, our whole experience is based on us being in a continuous exchange and with the physical world, the system where we are immersed in.

4.2 The Embodied Generative Music *Project*

Some of the paragraphs appearing in the following section and the next section "Embodiment as inhabiting" are based on the paper "On artistic research in the context of the project Embodied Generative Music" by Gerhard Eckel and David Pirrò, which appeared in the Proceedings of the International Computer Music Conference, ICMC 2009

The *Embodied Generative Music* Project was a research project hosted at the Institute of Electronic Music and Acoustics that run from 2007 and 2010: The project was funded by the Austrian Science Fund (FWF) in the context of its Translational Research Program. I could be part of the core research team comprising project leader Prof. Gerhard Eckel and researcher Deniz Peters. The project marked an important personal step as it was the first research project I could be involved in at the *Institute of Electronic Music And Acoustics (IEM)*. Further, this dissertation, its initial thematic framing and its conceptual and methodological foundation is strongly connected to the research issues addressed by the project.

The project's research questions and aims can be seen to base on early developments in electronic music and in live-electronics in particular. More specifically, an important step towards the direction taken in the project can be seen in the work of Joel Chadabe who used an early real-time computer music system to compose and perform his pieces Solo (1978) and Rhythm (1980) with two "proximity-sensitive antennas"[13]. The approach taken in these pieces he refers to as *interactive composing*. This concept has grown out of his work since 1967 and is very close to the idea of an *Embodied Generative Music*, i.e. a type of generative music informed by the dancing body during its unfolding.

Other important approaches related to the objectives of the *Embodied Generative Music* project (in the following EGM) can be found in the work of Todd Winkler and Wayne Siegel. Winkler used Rokeby's VNS[14] system to create what he called "motion-sensing music"[15]. Siegel explores "rule-based composition"[16] in the context of the DIEM Digital Dance Project[17]. With SICIB[18] a system "capable of music composition, improvisation, and performance using body movements" has been developed. As the technology has become more and more accessible over the past years, a great number of works that have more specifically dealt with the motion capture technology employed in *EGM* (although not in a performance situation) can be found in various contexts e.g. in gestural analysis and control[19]. Some of the questions raised by *EGM* touch upon movement sonification and therefore are also related to work in this field.[20]

The *EGM* project combined scientific and artistic research in order to further the understanding of the relationship between bodily and musical expression. In this endeavour, the research in *EGM* was driven both by a scientific and an artistic motivation. On the scientific side, the questions concerning the roles played by the body in music creation, performance, and experience were approached from the perspective of music aesthetics. It is common sense that there exists a close relationship between the two forms of expression, one of which usually appeals more to the visual sense (literal body movement) whereas the other one more to the auditory (metaphorical movement in music). As it turns out, it remains very difficult to characterise, understand and explain the various forms in which the two

[13] Joel Chadabe. Interactive composing: An overview. *Computer Music Journal*, 8(1):22-27, 1984

[14] David Rokeby / Very Nervous System: http://www.davidrokeby.com/vns.html (accessed 25/07/2017)

[15] Todd Winkler. Motion-sensing music: Artistic and technical challenges in two works for dance. In *Proceedings of the International Computer Music Conference*, pages 261-264, 1995

[16] Wayne Siegel and Jens Jacobsen. The challenges of interactive dance: An overview and case study. *Computer Music Journal*, 22 (4):29-43, 1998

[17] The Royal Academy of Music, Aarhus - DIEM:http://waynesiegel.dk/?page_id=214 (accessed 25/07/2017)

[18] Roberto Morales-Manzanares, Eduardo F Morales, Roger Dannenberg, and Jonathan Berger. Sicib: An interactive music composition system using body movements. *Computer Music Journal*, 25(2):25-36, 2001

[19] Frédéric Bevilacqua, Jeff Ridenour, and David J Cuccia. 3d motion capture data: motion analysis and mapping to music. In *Proceedings of the workshop/symposium on sensing and input for media-centric systems*, 2002; and Christopher Dobrian and Frédéric Bevilacqua. Gestural control of music: using the vicon 8 motion capture system. In *Proceedings of the 2003 conference on New interfaces for musical expression*, pages 161-163. National University of Singapore, 2003

[20] Alfred O Effenberg. Movement sonification: Effects on perception and action. *IEEE multimedia*, 12(2):53-59, 2005; Ajay Kapur, George Tzanetakis, Naznin Virji-Babul, Ge Wang, and Perry R Cook. A framework for sonification of vicon motion capture data. In *Conference on Digital Audio Effects*, pages 47-52, 2005; and Katharina Vogt, David Pirrò, Ingo Kobenz, Robert Höldrich, and Gerhard Eckel. Physiosonic-evaluated movement sonification as auditory feedback in physiotherapy. In *Auditory display*, pages 103-120. Springer, 2010

are related in experiencing music, and how they can be related in the creation of music. Thus, the main scientific objective of the project was to propose new elements of an aesthetic theory of the body/music relationship. This part of the project was mainly addressed by researcher Deniz Peters.

On the artistic side, the body/music relationship was approached from a *poietic*[21] perspective in the context of *performance-oriented computer music* (Garnett)[22], a kind of computer music which encompasses a strong performative element basing on the bodily presence and actions of a human agent. A main characteristic of this kind of computer music is the possibility to dissociate the performer movement from the sound production and make it thus subject to composition. This poietic option was introduced by audio technology invented in the late 19th century and further developed in the 20th century, especially since the rapid proliferation of the digital computer in the late 20th century. Although the various possibilities of body/sound dissociation (e.g. transmission and storage or real-time synthesis and transformation of sound) have been used in music creation for a long time now, the poietic questions associated with them are far from being clearly formulated, let alone them being systematically addressed or answered. The *EGM* project aimed at contributing to the sharpening of the questions associated with the *poietic* conditions of computer music production. In this sense, of central concern to the project was the question through which means and to which extent performers (especially dancers) may be able to shape the unfolding of a generative music composition through and with their living bodies.

In approaching this ideal through various routes, both the scientific (aesthetic) and the artistic (poietic) questions are addressed, acknowledging that they could not be treated separately. For instance, in order to make an aesthetic aspect appear in an experimental setting, poietic questions have to be addressed when conceiving the setting.

The *aesthetic laboratory* (*ÆLab*) was this setting and the research environment in which the EGM project has been carried out. Physically it was installed in a 120m^2 studio space equipped with a 24-channel hemispherical Ambisonics-based sound projection system and complemented by an array of 48 ceiling-mounted speakers. Besides the sound projection and rendering infrastructure, a 60m^2 dance floor and a *VICON*[23] motion-capture system with 15 infrared cameras is installed allowing for high-quality full-body motion tracking. Working in the *ÆLab*, the dancer leaves a complex "body trace" in time and space which

[21] The word poietic is used here to underline a fundamental quality of the perspective that has been taken in this strand of research in the *EGM* project, which is mostly based on productive tokens (from the Greek root of the term, *poieo*, "to make") and creative processes, as an alternative to a theory based approach.

[22] Guy E Garnett. The aesthetics of interactive computer music. *Computer Music Journal*, 25(1): 21-33, 2001

[23] Motion Capture Systems from Vicon. Available: http://www.vicon.com (accessed 25/07/2017)

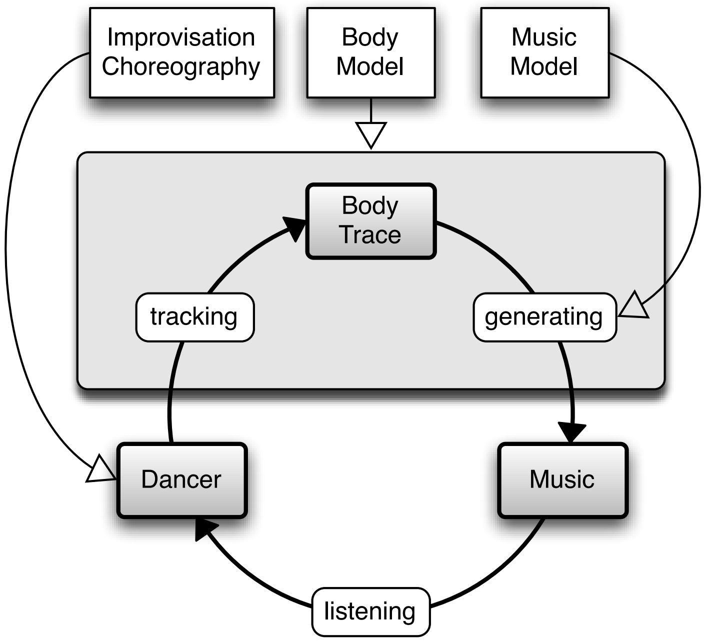


Figure 4.5: Schema of the conceptual and technical setup on the *Ælab*

is used to inform the generation of sound and music (see figure 4.5).

The "body model" is inherent to the tracking technology used (see figure 4.6). The "music model" represents the generative music composition. The resulting music naturally has a strong effect on the dance. In this tightly-closed loop, the dance is as much subject to the structure of a choreography and/or the dancers' improvisational skills as it is driven by the music unfolding as a consequence of the dancers' movements - i.e. a music the dancers perform themselves.

As such an endeavour would probably change - or at least shift - the established understanding of choreography, improvisation, and composition, we approached our goal step-by-step in order to tackle to complexity involved. We thus reformulated our problem in terms of building a new instrument that could be played by the dancer - knowing well that the terms "instrument" and "to play" serve only as auxiliary constructs, as we meant an instrument for playing on a structural level. An underlying assumption of this approach was that the expressive means and the bodily memory of the dancer's body would be best suited to fulfill our desires of an embodied generative music.

The first step in approaching our overall objective consisted in taking our instrument metaphor literally and have the body produce sound. This was achieved by directly mapping the tracking data to sound synthesis parameters, thus achieving a kind of sonification of the dancers

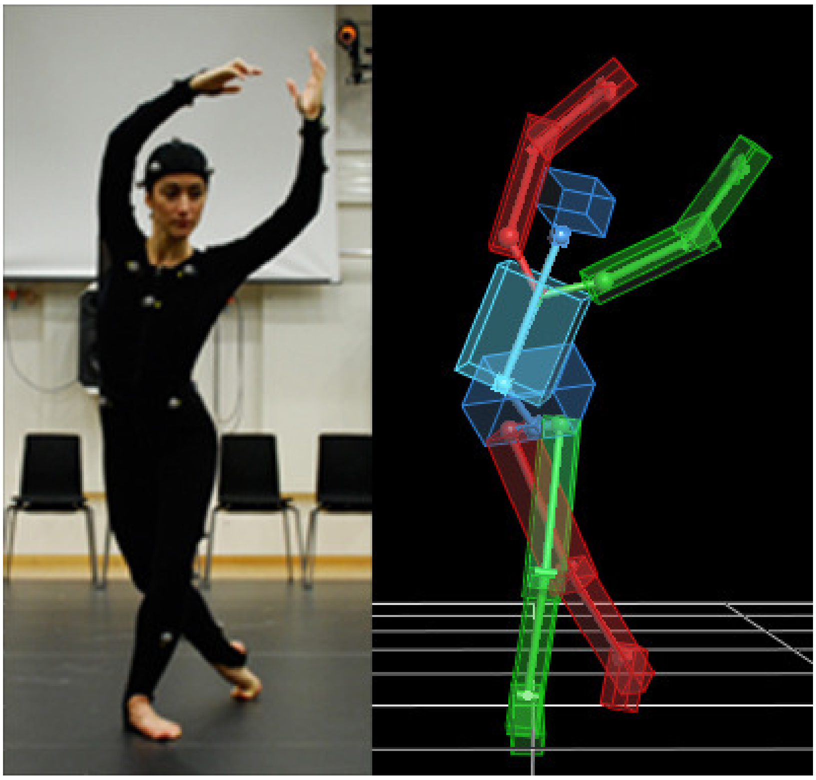


Figure 4.6: Dancer Valentina Moar in the full-body motion tracking suit (left) and the body model reconstructed by the Vicon motion tracking software

movements. Besides solving the underlying technical and practical problems of full-body tracking and interpreting the enormous amounts of tracking data, many new ideas and insights concerning possible approaches to the overall goal were generated in this step.

Methodologically this exploratory part was organised in smaller units of experimentation that we called *scenarios* (or also *case studies*). In each of those we tried to address one specific way to connect bodily movement and sound: each was therefore characterised by one particular mapping establishing such connection. The fundamental idea of the *scenarios* was to further subdivide the complexity of the "problem" we wanted to tackle in smaller units each realising simple, distinguishable and observable aspects. An analytical i.e. a systematic approach underlay this methodological structure that operated on the assumption that each aspect could actually appear in isolation.

Mappings were simple, but yet offered parameters to be adjusted during the experimentation phase with the dancers. Alterations of parameters in such essential mappings would cause sensible deviations of their aesthetic qualities. Implicitly following a sort of *variational principle*[24], such "differential" relations would allow to explore the "aesthetic space" of body/sound relationships. Eventually, this method would enable to establish a stable

[24] I use the concept of *variational principle* here in a metaphorical meaning: in *mathematical analysis*, the original context of the concept, it stands for a general method for finding the functions which satisfy certain (extreme) conditions. That is, in general the principle is used to determine the underling function given its observed variations relative to an independent variable.

connection between aesthetic experience and the mappings' formulation thus making it available for composition.

As it may be clear, our methodology was therefore strongly shaped by *Æsthetic Means*. Determining if and how a mapping was appropriate in eliciting a specific experience was guided by aesthetic criteria. Dancers can judge with high confidence if a sound model and its motion mapping fit the movement or not, i.e. if the change in the sound feels right for a particular movement with respect to realising a particular idea. Motion mappings were thus developed in several iterations of an empirical process, in which dancers and composer informally assessed and discussed the quality of the mapping using their own embodied perception (aisthesis). The main measurement instrument in the *ÆLab* is thus the aesthetic experience of the artistic researchers - hence the name of the lab. This experience, which is discussed among the researchers, is the basis for the aesthetic judgement that determines the path the process takes.

After an intense period of exploring various kinds of motion-to-sound mappings with different dancers, we felt the need to summarize our findings in a short dance solo piece, which became *Bodyscapes* (see section A.1 Bodyscapes in the appendix). In fact, there is a big difference to an experiment in a laboratory situation, in which we may abstract from many aspects which are part of the problem we are treating in order to concentrate on a few central one. One could say that trying to address "research-able" questions by producing and exposing artworks represents a sort of complication of the situation with respect to a more scientific approach which tries to reduce "disturbances" in order to possibly "measure" and analyse results. But, when producing a piece that follows an artistic idea, we are forced to acknowledge all aspects of the production and performance and their complex network of relationships and this will raise different questions, which otherwise would never be asked and answered. At least from an artistic perspective, these questions and the unrevealed perspectives they bear often are more valuable than quantitative results.

The piece *Bodyscapes* has a special place in this dissertation even if in fact there were no physical models or dynamical systems involved in its composition. I mention this work because the decision to produce and perform this piece and was methodologically motivated at that time and had a great impact on the way research in the context of this dissertation has been conducted after. Most of the research work I present here bases on experiences gained during the production of artistic works. I could say that the production, exposition and performance of artistic artefacts became, after this initial experience in *Bodyscapes*, a stable tool in the set of methods I have been working with. This method provided a sort of balancing counterweight to the *scenarios* approach and the more "analytical" perspective it embodies.

4.2.1 Embodiment as inhabiting

The overall objective of the artistic research in *EGM* was the development of new intermedial means of artistic expression combining dance and generative music, choreography and composition through new technology. There are a number of research questions which arise from this overall goal. But the core of the whole project, its driving force was the Utopian concept of an embodied generative music. Therefore, a central question was in which manner may the dancer's movement influence the unfolding of a generative composition in an intuitive, i.e. *embodied way*.

The project grounds on the concept of an *embodied interaction* (see 2.3 Embodiment) framing the perspective taken in observing and developing relationships between the dancing body and sound. Interpretations of how *embodiment* might be defined are numerous and can vary strongly depending on the research context in which they appear. In the context of the *EGM* project we would understand *embodiment* as:

> *the extension of the dancer's body into the music - both on the level of the sound production as well as on the level of the unfolding of the compositional structure.*

We used the word *inhabiting* to describe this essential quality of the relationship between the dancing body and a musical composition. We imagine the dancers to be able to inhabit the music (as well as their dance). By this we meant they would know it well, feel "at home" in it, they would feel at ease navigating it, they would be able to achieve a symbiosis of movement and sound, of dance and music, of choreography, improvisation and composition.

The understanding we reached with the dancers is that a scenario can be thought of as a kind of "sound costume". In this sense, a successfully composed scenario has to be "wearable" by the dancer. Wearing the sound costume will - similar to a real costume - highlight certain features of the movement and it will suggest to move in certain ways, to use the sound-extended body in a certain way. It may also constrain the movement strongly, which may or may not suit the artistic and aesthetic idea.

With respect to the sound production *EGM* offered the dancer a kind of virtual instrument. For the dancer to be able to "inhabit" this instrument, a number of requirements have to be met, some of which were assumed essential at the outset of the project, others were identified during the course of the project.

- Real-Time Requirements: Richard F. Moore's term "control intimacy"[25] denotes a concept very useful in illustrating many of the requirements that have to be met in order for an embodied sound generation to become accessible to a dancer. In his paper, Moore focuses on the temporal aspects of the problem - the time lag between performer action and audible result and the jitter of this time-lag. Both are very important in the case of *EGM* - the time-lag had to be as short as possible and the jitter as small as possible. In the EGM setup we worked with a time-lag of less than $20ms$ from movement to sound and a jitter of no more than 5%. These values were measured with a *VICON* system comprising 15 M2 cameras covering a tracking volume of about $100m^3$ and running the iQ2.5 software. In most cases, a tracking rate of $120fps$ was used at which the position and orientation data were provided by the system. Higher rates would have been possible at the cost of a reduction of the spatial resolution of the system, which was soon found to be essential for embodiment to occur. At $120fps$ the system resolved positions in three-dimensional space with a precision of about $1mm$.

[25] F Richard Moore. The dysfunctions of midi. *Computer music journal*, 12(1):19-28, 1988

- Real-Space Interface: As much as we had to provide the dancer with a real-time interface, the interface was also required to qualify as a real-space interface. Only the mentioned spatial resolution and its consistent availability throughout the whole tracking volume could guarantee that also the most subtle movements of the dancers would be captured and translated into sound. The noise introduced by the system described here is of the same order of magnitude than the noise inherent to a dancer's body - this being a minimum requirement for embodiment to occur with most types of mappings, especially, of course, with space-based mappings. This aspect has been described very well by David Wessel, when he writes:

  Musical control intimacy and virtuosity require both spatial and temporal precision in the sensing of gestures.[26]

  Another requirement for the dancers movement to be kept intact is the availability of position and orientation

[26] David Wessel. An enactive approach to computer music performance. *Le Feedback dans la Creation Musical,Lyon: Studio Gramme, France*, pages 93-98, 2006

information with the mentioned resolution for all body segments in order to allow for a sufficiently detailed and fully three-dimensional representation of the dancers instantaneous posture. The quality of the posture representation has to be independent of the dancer's position and orientation in the tracking volume. The overall quality of a real-space interface is determined by its spatial precision, the size of the tracking volume covered, and its reliability (the system has to be able to track any posture a dancer may take).

One of the most successful scenarios in the *EGM* project was, departing from the above instrumental qualities, the so-called *Springer-Tempophone* scenario. In many explorations it showed to offer dancers the affordances for being "inhabited", and was the basis for many other scenarios developed during the project as well as for some scenarios in the *Bodyscapes* piece. In its most simple incarnation, the mapping this scenario employs, uses the tracked value of the position along one of the Cartesian axes the tracking system draws into the space, e.g. the x value of the three dimensional positions of the right hand of the dancer. The mapping function then appropriately scales this value and transforms it into an index into a pre-defined sound file, i.e. a space coordinate is transformed into a time coordinate. A granular synthesis algorithm, given this time value, "extracts" a small window, a sound "grain" 100*ms* to 22*ms* long around that index from the sound file and reproduces it in a loop. Changing the hand's position would cause an update of the window's position in the file and therefore a different sound grain would be reproduced.[27] The sound synthesis realises a sort of *Springer-Tempophone*[28] mechanism, an analogue tape recorder/player which allowed to independently control playback speed and transposition.

Basically the scenario realises a most simple connection between position in space and sound: moving in space means also to traverse and hear the sound contained in the file. Further, the *real-time* and *real-space* qualities of this instrument made this connection to be as *direct* as possible and therefore interacting with the body's own spatial and temporal perception's allowing for embodiment as inhabiting to emerge. As a clear example, dancers repeatedly reported how strongly the sound in the recording structured their spatial awareness and even described how they experienced virtual haptic illusions[29].

[27] In its condensed form, this description attempts to transport the essential idea of the scenario. Still, mapping and the sound synthesis process were a bit more fine-tuned in every different version. For instance the length of the window was related to the height of the tracked joint in order to provide for a broader sound colouring; further the central position of the grain was very slightly jittered so as to avoid the sonic artefacts which would appear when reproducing exactly the same sound bit in a very short loop.

[28] Peter Manning. *Electronic and computer music*. Oxford University Press, 2013

[29] Jana Parviainen. Seeing sound, hearing movement. In Deniz Peters, Gerhard Eckel, and Andreas Dorschel, editors, *Bodily expression in Electronic Music*, chapter 5, pages 71 - 81. Routledge, 2012

4.2.2 From embodiment to enaction

The experiences we have collected in the *Ælab* have shown that the conditions may be created for the dancers to actually extend their bodies into the instrument, that is to actually *embody* the sound synthesis processes, in the understanding I've described in the previous section. This could be realised by establishing direct or mostly unmediated sound to movement connections. But, those scenarios where limited to a rather *instrumental* understanding of the body-sound relationship: to a body state or movement a sound is being associated. Looking back now at the project I might safely say that it did not manage to realise its utopia of an *embodied generative music*, a form of interactive generative music which would allow dancers to embody the process, the algorithmic model by which music is generated and not just the details of sound synthesis. Still, some of those experiences, especially the ones driven by an artistic approach as during the production of the piece *Bodyscapes*, forced a re-thinking of the project's assumptions and revealed different perspectives that otherwise were not foreseeable.

The most important of these moments, one that triggered many thoughts and questions that only now, after years, may become clear, is connected with what called the *delay scenario* which appears in *Bodyscapes* as *The Partner* (see Bodyscapes). The scenario departs from the above mentioned *Springer-Tempophone* scenario introducing two critical modifications.

The first consists in a delay of a few seconds (e.g. 4 seconds) introduced between the dancers' movements and the sounds which would be generated as an immediate consequence of their actions. Dancers would move without instantly hearing that movement's sound, instead they would hear it after some time. As they start to move in response to this material they would in turn generate sound which will then appear only in future.

This modification breaks therefore the immediacy relationship between sound and movement with respect to the instrumental condition addressed before. A mediation step, the delay, is introduced between action and sound provoking a radically different situation where cause - effect linkages are forced to undergo a perceptual re-interpretation. A key observation is that this transformation appears to be possible on the basis of the bodily agency dancers would still hear inscribed into the sound; their own delayed agency. This hinted agency gives the sonic output consistency allowing the construction of a coherent perception. Even if the mediation impedes it, the "reaction" of the computer music system does not therefore appear as random or unaffected by their actions. The heightened proprioception and bodily memory further allows dancers to reconstruct a path into the past and consequently to actually project into the future sounds with the actions they are performing in the present, sounds to which they will dance[30]. A sort of play between expectation and correspondence can be experienced not only by the performers, but also from the audience. As this play was taking place on a temporal level, even if admittedly only simple articulations of action / reaction and repetition / difference seemed possible, the delay step showed a possible perspective into an interactive environment which could act on sound organisation in time.

[30] The dependence of the dancers' ability to cope with this situation with the length of the delay has not been studies systematically. Nevertheless, it is to expect that delay times approaching short-term memory duration (~ 18 seconds) would cause a sensible degradation of their capacity to reconstruct temporal relations.

Now, a further parameter is added to the scenario. The delay time is made variable and dependent on the speed of the performers' tracked joint. The dependence is inverse proportional; meaning that if the speed is minimal the delay is maximal (e.g. 4 seconds), while when the speed is at the maximum[31] it is minimal (e.g. 0 seconds), i.e. sounds are produced immediately; the changing delay value is smoothed with a simple integrator (low-pass filter). The synthesis process does not compensate for the delay variation: as a consequence, the dancers' movement articulations produce pitch shift effects clearly audible in the produced sound. Accelerating actions mean diminishing delay times, causing the delay line's "read head" to move towards the "write head" and therefore speeding up the reproduction of the sound in the buffer eventually producing an upward transposition. On the contrary, a deceleration would drag the read head more toward the past, far from the current sound meaning a deceleration of sound reproduction and thus as transposition to lower frequencies.

[31] The value of maximum speed has been determined experimentally and adapted to each performer.

As, in contrast to the effect of the delay, these artefacts appear instantly as the movements' articulation change, in this version the scenario unites both mediation and immediacy. Anyway, these two aspects are non-trivially interwoven in such way that acting independently on one or the other is not actually possible.

The scenario presented performers with an environment whose responses and temporal behaviour are far from the qualities of interaction we had searched for and experienced before. It was a situation which was difficult to grasp rationally or analytically; no certainty as to which output an input would correspond; without the addition of the variable delay this was still possible, but at this point there was no clearly reconstructable cause - effect relationship. Rather, the sensibility of the system to both present and past events would induce variations in the output depending on the whole history of events preceding that moment, thus making every movement unique and almost non-repeatable. In a sense the scenario had all the characteristics which we didn't want: it wasn't simple nor it did present a clear and direct correlation between movement and sound.

This scenario clearly was more complex[32] then any other we had tested before. It was striking that a relatively small change in the algorithm induced such profound effect on this scenario. Also in light of the previous explanations, this might seem an obvious observation: even a small change in a simple set of rules of an algorithm have the potential to produce unexpected and unforeseeable results. Still, experiencing this so dramatically actually evidences how fragile a controlled situation can be, how delicate and not at all stable such a situation can be. And moreover, how interesting this instability is.

[32] The term *complex* here is used to indicate a situation consisting of multiple interwoven and mutually interdependent variables.

Even more unexpected was that dancers could cope with this complexity. They could enter the scenario and establish a relationship; they could dance with it. Even if it was at best confusing when looked at with rationalising attitude, they could apparently "read" it with their bodily perception. They could "*grasp the dynamics of the system with their bodies*[33]" as Gerhard Eckel puts it describing this scenario.

[33] Gerhard Eckel. Embodied generative music. In Deniz Peters, Gerhard Eckel, and Andreas Dorschel, editors, *Bodily expression in Electronic Music*, chapter 10, pages 143 - 151. Routledge, 2012

Dancers engaged in a performance continuously oscillating between action and reaction, togetherness and opposition. The sonic reactions where unpredictable, but they still exhibited a coherence, a felt *agency* or a *behaviour* which could be grasped both by dancers and audience. This aspect contributed to a crucial aesthetic change of perspective: the computer music system appeared as an actor in the environment, a source "external" to the dancing body. No, two actors were on the scene, exchanging, at times struggling, exhibiting different and changing modes of interaction fluctuating between synchronicity and conflict. As such, the performance itself emerged as a process generative of different aesthetic experience of the connection between body and sound. It was the nearest to the imagination of an *embodied generative music* I could say to have seen during the project and I would say artistically one of the most rewarding experiences of the *EGM* project, both for the dancers as for the audience. In the attempt to understand how this scenario would fit into the project's frame, new questions have been provoked which demanded consideration. How could this situation be interpreted in terms of our understanding of *embodiment*?

Juxtaposing this scenario with others previously developed, reveals some implicit aspects and limits of our approach.

Aiming at essential and traceable aspects of the connection between bodily movement and sound we employed mappings establishing a simple and direct relation between the two. In retrospect and at a closer look, I would say that the paradigm we were still implicitly relying on was that of direct and unmediated *control*. We thought of the entire situation in terms of a traditional musician / instrument relationship where virtuosity is directly proportional to the detail of control musicians would exert on the instrument. Our assumption was that this kind of control was the substrate which would offer the right affordance for the body to grow into the sound, to embody it. The *delay scenario* showed us a different mode of interaction transcending the limits of this assumption. It was clearly perceivable that performers were *not in control* of the details of the situation; neither they were completely disconnected or non-interacting. Actually, issues of control (who is in control? who is acting upon who?) did not play a role for them and for the audience. A central concern therefore materialises: how much do (implicit or explicit) *control* paradigm inhibit possible alternative perspectives on interaction. And possibly what concept could replace it and better fit?

Our idea of *embodiment* as inhabiting the sound synthesis which would become a "costume" for the moving body, actually involves the dissolution of specific qualities of the "other" element, those which would make it appear as an artefact *present-at-hand* in Heidegger's language. Ideally, the computer music system would then be a transparent interface completely permeable to the (total) control of the performer. In the *delay scenario* instead, both actors retained their "identity": it is "as if the music were an other creature dancing with her[34]", as Susan Kozel writes in describing how dancer Valentina Moar performing in this scenario[35]. They *resisted* each other, but did not dissolve: this is a central aspect to this scenario. Thus, our idea of *embodiment* reveals to be insufficient in describing and framing the mode of interaction this scenario exhibited.

An *enactive* perspective offers an alternative. The *enactive* approach (see 2.4 Enaction) holds that cognition is the result of a mutual, ongoing interaction between two entities. Performer and environment, both provided with *agency*, engage in a circular relationship. A temporally evolving connection in which the action and perception functions of each are interlocked. From this perspective, the *delay scenario* can be seen as the "representation" of an *enactive* process. Dancers are continuously challenged and "pushed" towards a re-adaptation of their bodily

[34] Susan Kozel. Embodying the sonic invisible. In Deniz Peters, Gerhard Eckel, and Andreas Dorschel, editors, *Bodily expression in Electronic Music*, chapter 10, pages 61 - 70. Routledge, 2012

[35] This specific performance took place during the symposium *Bodily Expression in Electronic Music* (*BEEM*) which was the final event the the *EGM* Project, held in November 2009.

understanding of the environment's responses. Experiencing this scenario from the audience's point of view, means to observe the (continuous) unfolding of the dancers' (and the environment's) cognition.

Apparently the scenario seems to offer the affordances of being such an environment, of possessing the "kind" of agency or behaviour which affords this particular *enactive interaction* mode to emerge. On the one hand, an agency which in itself is not too dependent on the performers and therefore not possessing a clear identity: the scenario would in this case fall into a "one actor" mode, with the computer music system reduced again to a merely reactive machine, an instrument. On the other hand, not too "free" from external influence: the effect of the dancers' actions should not be too small in order to allow for a perceptual correspondence to be established to the variations of the system's output: in this situation the scenario would risk to fall apart into the parallel performance of two independent actors.

With the *delay scenario* we have found, through an empirical process of calibration and testing, the "right" middle ground between these two possibilities. We can assume that a crucial factor in structuring the system's output appropriately is the fact that its temporal articulation contains the dancer's body own agency; transposed and distorted but still recognisable enough to provide the scent of an agency. Probably the most important quality of this trace being that such temporal articulation moves in a range of variability still ascribable to a body.

Crucially, this scenario and the switch to an *enactive* perspective, opens new ways to conceive and develop interaction in computer music praxis and performance. Ones that allow generative processes to become "tangible" and permeable to performers' actions on a structural level, rather then an instrumental. Therefore, pursuing this direction, the question at this point is to which extend and with which conceptual and practical tools could such agency by *composed*, not just found. Furthermore, which could be the conceptual implications of this *enactive* approach.

4.3 Dynamical Systems Thinking

Departing from the experiences made in the *EGM* project and especially with the *delay scenario* (see above), a move towards an *enactive* perspective on interaction would seem to allow an integrative view on both the bodily aspects of performance and the intrinsic generative computer music processes. This move is motivated by the observation that *agency*, as a perceived quality of the computer music system, would play a critical role in constructing and defining interactive scenarios: agency is an essential ingredient to the theory of enactive cognition.

It seems important to recall and clarify here that at the core of this inquiry is the question how computer music systems can be interactive and which are the conceptual and performative consequence of the development and composition of these systems. The understanding of computer music systems I employ here is not limited to an instrumental one, but includes and centres on the *generative potential* of algorithmic processes such systems may spawn. Further, *interactive* here means that those systems, formulated for musical performance and composition, should afford an involvement of the performing musician or composer they are put in connection with, which transcends an attitude of *control*. Rather they facilitate and require a deeper cognitive and physical effort by tapping into the very constitutive building blocks of perception. In this sense, I regard this research as a continuation on slightly different premises, of the *Embodied Generative Music* project from which the core research themes are inherited.

In the previous parts of this chapter, the term *behaviour* has been used for referring to a distinguishing temporal evolution e.g. of simulated physical models. The intuition behind this section, is that this idea of behaviour as in general exhibited by dynamical systems (of which physical models are a subclass), correlates strongly with the idea of an agency as observed and imagined in the *EGM delay scenario*. Following this path a collision is staged between the two concepts on the grounds of the definition and characterisation of agency as it can be found in enactive cognition theory (see 2.4 Enaction). I expect that this convergence would bring forth a sharpened definition of agency as the quality of a computer system which sustains interaction on the level of processes rather then on the level of states. The intent here is to refine a formulation allowing to stabilise a conceptual thinking framework which would also offer a concrete tool set for actual realisations.

To perform this collision, at this point a more or less precise definition of *behaviour* is needed. At least a clarification of the meaning the term has in the context of this dissertation. I borrow the term behaviour with the meaning it has in physics or mathematics, disciplines which also lack a clear definition of the term. In these fields, behaviour is used to indicate the "how" a function or a system evolves from one point or state to another. For example how the function $1/x$ reaches 0 when x tends to infinity is a behaviour proper to that function and to that function only. Or how the velocity of a mass m attached to a spring changes periodically in time, is the behaviour specific to that system. With behaviour I denote the way the state of a system changes from one moment to the next, from one coordinate to the other. It indicates the unfolding of change, the time ordered variations of a system when it proceeds from one state to the other. It is constructed by differences produced by the system being observed in dependence on the conditions it is placed in. Most importantly, behaviour is an identifying characteristic of a particular system: that is, all oscillators (e.g. mass-spring systems) exhibit similar and recognisable behaviour and every oscillatory behaviour may be ascribed to the evolution of a dynamical system of the "mass-spring class".

What I am trying, is to establish a bridge between dynamical systems and aesthetic and perceptual qualities. On the one hand, behaviour, in the "definition" above, I state that the path of evolution of a system, its particular temporal unfolding is a perceptible quality of that particular object or system as for example "colour" might be. On the other hand, there is the idea of behaviour in the sense it has in physics or mathematics and inscribed into precise mathematical formulation. Of course, these two meanings do not have to coincide and it is not my intention to equate them: still, as in both cases the word behaviour refers to the temporal structure (or dimension) of things[36], I attempt to establish a correlation between the two fields of dynamical systems modelling and the enactive cognition theory. The final (and maybe Utopian) aim being to develop a language for formulating behaviours which could be translated into programs or algorithmic entities: mathematical formulations offer this possibility.

[36] And in some way exploiting the somewhat unclear meaning field which the term covers in both contexts.

To be clear: I do not assert that any perceived behaviour can be readily transposed into a mathematical formulation of a dynamical system. The assumption here is that *the temporal behaviour of a mathematically formulated dynamical system has a perceptible correlate*. Most of the works collected in the Appendix (see appendix A, A catalogue of works) might be seen as experimental (and experiential) studies in which the former statement is put to test in different gradations of intervention by an external performer. That is, those range from interactive performer-system settings, to reactive installations, to acousmatic pieces which evolve with no or little influence of a performer. The qualities of perceived behaviour are the central aspect explored by these works an their connection to the underlying formulations in terms of physical models or, in general, dynamical systems.

Now, as anticipated, I attempt to bring together the two terms of behaviour and agency on the basis of the characterisation of the latter given in enactive cognition theory. Three qualities are fundamental: *individuality*, *activity* and *adaptability* (see section 2.4 Enaction).

1. INDIVIDUALITY: The system exhibits a clear and perceivable identity. Following experiences made in multiple artistic case studies, this characterisation strongly resonates with a sensible quality of the behaviour of dynamical systems I have often described using the term *coherence*. What I would like to delineate with this word is the felt consistency of the system's evolution: that is, the perception that the temporal path drawn by the sequence of states which lies between two chosen points A and B has "something in common" or is similar to the evolution from B to a later point C. It corresponds to an intuition of a constant evolution rule which lies "behind" that path, that is driving the system. In some way it is an affordance the system's evolution presents of *integrating* a sequence of states into a perceptual *image* (see also 3.4 A sense for change: behaviour).

   In some way, the former formulation affirms that the differential equations governing a dynamical system, can be perceived: not exactly formulated or reconstructed in a mathematical form, but sensed in their presence (or absence) and in their specific characteristics. Not only the specific way dynamical systems structure time seems to be perceptible, but also it contributes to the ascription of identity in that it can be differentiated between different systems. This form of perceived identity might therefore be also brought in relation with the specific form of the geometrical flow a dynamical system inscribes into *phase space*.

   This observation seems to be valid both in the case of isolated systems and while considering systems in interaction with an external agent or performer. *Coherence* in the latter case, I would describe as the felt consistency of the effects with their causes. That is, even if the effects exhibited by a dynamical system as a consequence of action are not always exactly the same or precisely predictable, they can be clearly brought into a sound relation: the "surpuls" of non-predictability can be ascribed to the system's agency or individuality.

   A further observation that dynamical systems yield a space of potential behaviour which is not infinite: even if there is a wide range of possibilities, viable paths lie in a bounded space: not every temporal evolution can be followed or produced by the system. This seems a fundamental quality of such system and is essential to the perceptual construction of an identity. If every behaviour would be possible, no underlying coherence could be reconstructed: limitations and constraints seem an indispensable ingredient.

Concluding: temporal behaviour, as it is generated by a dynamical system, can be brought into relation with a perceived quality of identity of an agent.

2. ACTIVITY: An agent is a source of energy for the coupled system, that is it acts also in absence of an external excitation. On the contrary, an agent "does something", it is a source of excitation for the environment it is in.

   This can be regarded as a fundamental difference to the systems I have describe before in this chapter, namely the *simple spring mass scenario* (see section 4.1.2 An example and some considerations) and the *delay scenario* (see 4.2.2 From embodiment to enaction). In both of those cases, the interactive environment the performers were confronted with produced reaction to input which were decaying over time. In the first example, due to the system's attrition setting, the spring's oscillations would fade away. In the second case, if the dancers would not move, the computer music system would not produce any sound by itself.

   Still, it seems quite obvious to ascribe a certain degree of independence and action to a process if it should be perceived as agent. Further, *activity*, in the sense of the synthesis of an acoustic output independently of an input, might be seen as a precondition if the focus lies on generative processes as they are understood in computer music. That is, processes that given certain rules, unfold their own temporal structure.

   Experience with artistic works has shown that dynamical systems might well be modelled and simulated such that they would be source of activity, generative in a computer music sense. In terms of the mathematical formulation, from this activity requirement would follow that such dynamical system would not have an asymptotically stable fixed point in the origin (see section 3.1 Theory): from the presence in the system of such type of critical point would in fact follow that the system would, sooner or later, "fall" and remain in that state indefinitely, or at least until re-excited again. That is, the system would be built around a more instrumental conception. A simple attractor which would fit this description would be the centre attractor, which paradigmatic for oscillatory phenomena e.g. the undamped oscillator or the *limit cycle* attractor.[37] At least the system should posses a lower bound for the energy which would prevent it to fall into a fixed point and not move anymore.

The activity quality therefore means a narrowing of the possible behaviour types and implies dynamical systems which have no asymptotically stable critical points.

[37] At present it is unclear if from the request of activity in the sense described here, together with the condition of boundedness (i.e. the state of the system cannot become infinite) would strictly mean that the attractor types and behaviour addressed here can be only be oscillatory. This aspect should be addressed in future research.

3. ADAPTABILITY: This quality refers to the connection the agent has with its environment or the other actors in it, in which way this relations may influence it. As adaptability posits a *coupling* of the agent's system with the environment and therefore addresses the role of action and reaction, of *interaction* for the agent system. This aspect is therefore of central interest here.

   From the perspective of dynamical system's modelling, adaptability requires the behaviour of the system to be influenced in some way by the state changes of the external environment or other agents it might interact with. How can this influence be better formulated? It is clear that an external input affects the system's behaviour, but how can this happen? With reference to the diagram 2.3, in which way the bottom coupling arrow enters the system's constituting process? A good example is here again the *simple spring mass scenario* (see 4.1.2).

   As a dynamical system, we are looking at a simple linear system, which might be written as:

$$\dot{\vec{u}} = A\vec{u} \tag{4.7}$$

   where $\vec{u} = (x, v)$ is the state vector of the system, x and v the position and the velocity of the mass respectively, and A is the *Jacobi* matrix:

$$A = \begin{pmatrix} 0 & 1 \\ -k & 0 \end{pmatrix} \tag{4.8}$$

   With this definition this formulation would therefore reduce to equation 3.9. Extending the dimension of $\vec{u}$ and modifying A according to the problem at hand, equation 4.7 is a valid formulation for any general *linear* and *autonomous* dynamical system (see section 3.1 Theory). Including the external influence on the system i.e. the moving and tracked hand position in the example of the *simple mass scenario* (see 4.1.2), means to include in this formulation a *time-dependent* external component.

$$\dot{\vec{u}} = A\vec{u} + G(t) \tag{4.9}$$

with $G(t)$ a function which for this simple example could be re-written as:

$$G(t) = \begin{pmatrix} 0 \\ kx_h(t) \end{pmatrix} \tag{4.10}$$

where $x_h(t)$ is the (time-dependent) function of the hand's position.

The inclusion of the external influence $G(t)$ on the system, from a mathematical perspective has a qualitatively dramatic effect on the type of problem we are now concerned with. Mathematically any such system would now become a *non-autonomous* dynamical system. This category of problem has completely different qualities then the previous. Even if the form of the function $G(t)$ would be known in advance, they are much more difficult to "solve". In general, for most of these problems, one cannot find mathematical solutions at all: strange attractors and chaos lure at every corner. The only possibility is to simulate such systems: that is, to computationally evaluate the system's state time step by time step in order to actually "see" or re-construct an image of its behaviour. And this is what we do here, especially as in our case the form of the external input's function $G(t)$ cannot be known and is dependent on the performer's actions.

Now, having this formulation, another important consideration can be made. From the example of the *simple spring mass scenario* and the formulation we have found above, one can see that the external input enters the system by modifying its *flow*: that is, it influences how the system will evolve in time. Typical coupling models, or more commonly mappings, between external action and computer music system would consist in a functional relation of some kind between input and internal *state*. Returning to our previous example, this would mean that moving the tracked hand would produce a change in the state of the simulated mass, e.g. by directly translating it, placing it instantaneously onto another phase state path. In the present case, such kind of approach would actually mean to momentarily (for the duration of the input) suspend the system's own behaviour in order to set it into the desired state.

In light of the previous discussed qualities of identity and activity, a direct manipulation of the system's state should therefore not be allowed. It would mean to be able to suspend, even if partially, its identity and its own activity in order to act on it applying an instrumental control. It would further mean to apply an ideally infinite force to the system from an external "god-like" view on the system. No equal partnership between a so composed computer music agent and a performer, like that seen in the *delay scenario* (see 4.2.2), could then be realised on these grounds.

Instead, influencing the system on the level of its evolution, would allow its output coupling (again referring to the diagram 2.3), being function of its state output then, to carry both a sign of the internal dynamics and of the effects of the input. Perceiving or hearing both these aspects in the system's output is, as various experiences have shown, fundamental for the understanding of the agent's behaviour. Again taking the *simple spring mass scenario* as model, the performers moving their hand would induce an output response that is determined both by the system's own dynamic and by their input. That is, the performers are enabled to perform a sort of *perceptual impulse response* testing of the system, by listening to the effects of their actions *through* the system's output and therefore re-construct an "image" of the system's internal dynamics. Of course, when the systems composing the agent get more complex, non-linear and *active* in the sense explained above, it is not possible to speak of an impulse response testing in a traditional sense, i.e. as in signal processing. Still, I believe that as metaphor the idea holds for the purpose of explanation.

Returning, to our starting point, the question of adaptability, we see that this quality refers to much more than only the nature of the agent's coupling with the environment. In fact, adaptability also indicates the agent's ability to *modulate this coupling*. According to the enactive cognition theory, this modulation is performed by the agent aiming at maintaining its *norm*, which in general corresponds to the self maintenance of the processes which constitute it (see 2.4 Enaction). Further, this modulation has to be a function of the system's state. In terms of a dynamical system and extending the previous formulation at equation 4.9, this would mean:

$$\dot{\vec{u}} = A\,\vec{u} + H(G(t), \vec{u}) \tag{4.11}$$

where H is the function modulating the effect of the external input G into the system, and is not only dependent on time, but also on the state vector $\vec{u}$. In general, we can assume that the function H, the time-dependent modulation of the system's coupling with the exterior, should again be a dynamical system. With this change, the above system becomes not only non-autonomous, but also *non-linear*: even if supposing a very simple linear system at the core of the agent's behaviour (e.g. in the example above) as a consequence of the request of adaptability, this system is drawn again into a qualitatively different class of dynamics. The behaviour it could exhibit, especially in concert with the external environment or agent, would be qualitatively different: complex, emergent and chaotic.

4.3.1 Phase Space Thinking: an experiment

In the preceding sections a better understanding of the concepts of agency and behaviour has been gained as well as their reciprocal connections have been delineated. At this point a fundamental question can be addressed: *How can agency and behaviour be composed?* More in detail, grounding on the previous insights in how the specific definition of enactive agency could be reformulated in terms of dynamical systems behaviour. Or, in more detail: *How can dynamical systems be composed such that their behaviour generates agency? How can these dynamical systems be employed in the composition of interactive computer music environments?*

These questions aim thus at the development of tools or a framework that allows to realise the ideas above, to put those to test in practice or at least explore the space of possibilities they could provide. At this point we lean on an established and existing tool used to observe and analyse dynamical systems qualitatively: the *phase space representation* (see 3.1 Theory).

This representation reformulates the systems of differential equations defining dynamical systems into geometrical structures, so-called *attractors*, spatial movements and *vector flows*. These representations have the indubitable advantage to transport abstract mathematical formulations into a realm of more directly sensuous experience. They provide an alternative access to the qualities of dynamical systems which bases on the visual sense: relying on my experience, I would claim that the figures and diagrams which live in this space seem to have an immediate bodily correlate. By looking at those, one gains a sense of what a dynamical system is "up to". These qualities of the phase space representation can be readily experienced when looking at the well known book by mathematician Ralph H. Abraham and visual artist Christopher D. Shaw: *Dynamics, the Geometry of Behavior.*[38]

It is important to note here that the representation phase space provides of a system's behaviour is not just a more or less faithful "picture" in geometrical terms.

[38] Ralph Abraham and Christopher D. Shaw. *Dynamics-the geometry of behavior*. Addison-Wesley, Advanced Book Program, Redwood City, Calif., 1992

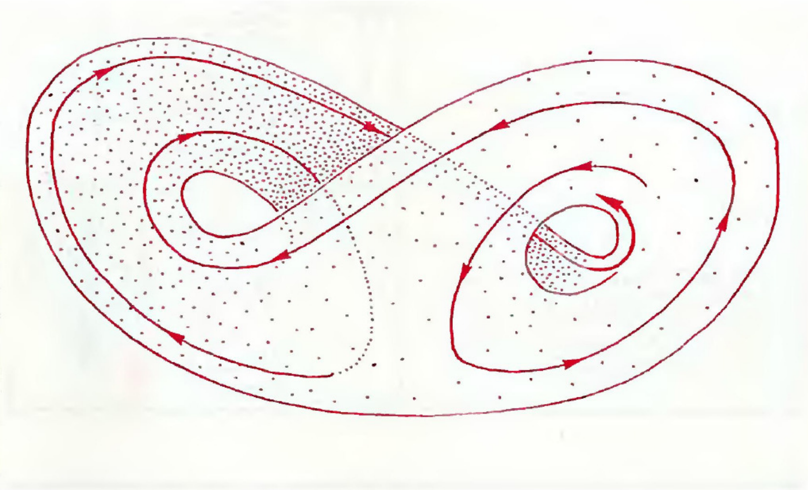


Figure 4.7: One of the lorentz attractor's phase space representation: Abraham Shaw *Dynamics - The Geometry of Behavior*, p. 286

It is well known that phase space and the mathematical formulations using systems of differential equations are *isomorphic*, meaning that they contain exactly the same information: they can be used alternatively.

Phase space and in particular the "construction" of the *Lorentz attractor* as it is depicted in the book cited above, might serve here as a metaphor for illuminating again which Utopia I am following in pursuing this path.

With reference to the following figures, we may look at both the computer music system and the performer as two, at first, disjoint dynamical systems (see figure 4.8). We may regard the first two dynamical systems (performer and computer music system) as being of some type *A*, (three dimensional attractors of saddle type with spiral outset in the figure). A second attractor *Y* (a saddle attractor with nodal dynamics on its inset in the figure) could then be the phase space representation of the dynamical system of the coupling between performer and system.

Now, setting two *A* type attractors (a performer and a computer music system) in the same phase space, their mutual interaction through their coupling *Y* will provoke a transformation and deformation of the phase space flows exerted by the individual attractors into a global flow (figure 4.9). Eventually a new attractor emerges affecting the whole phase space.

This operation of combination produces therefore a new unitary and complex structure, a new dynamical system: the single attractors from which we departed are still there, but reciprocally modulated by the other systems occupying the same space. Still, their intertwining produces something new, which cannot be decomposed into a sum of the effects: the single attractors are instrumental in generating this new system, but at the same time they

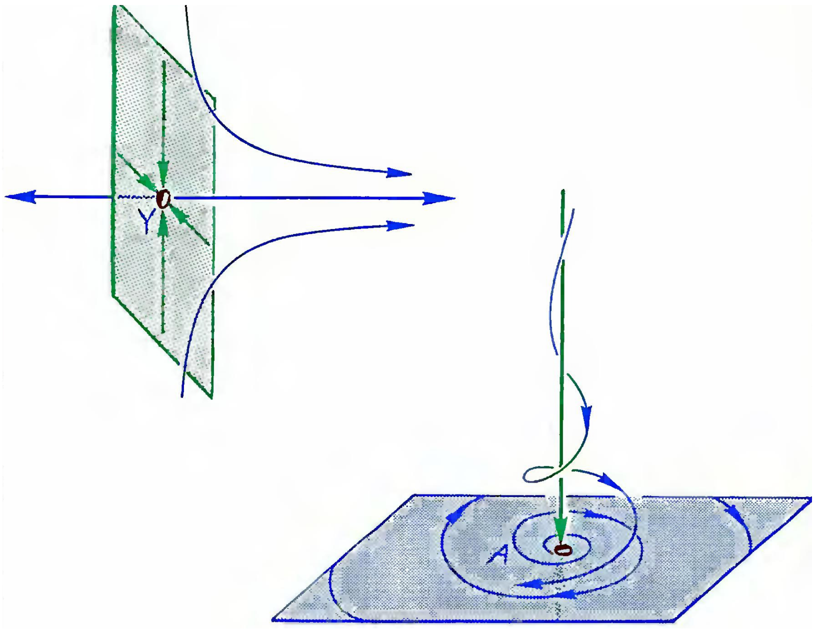


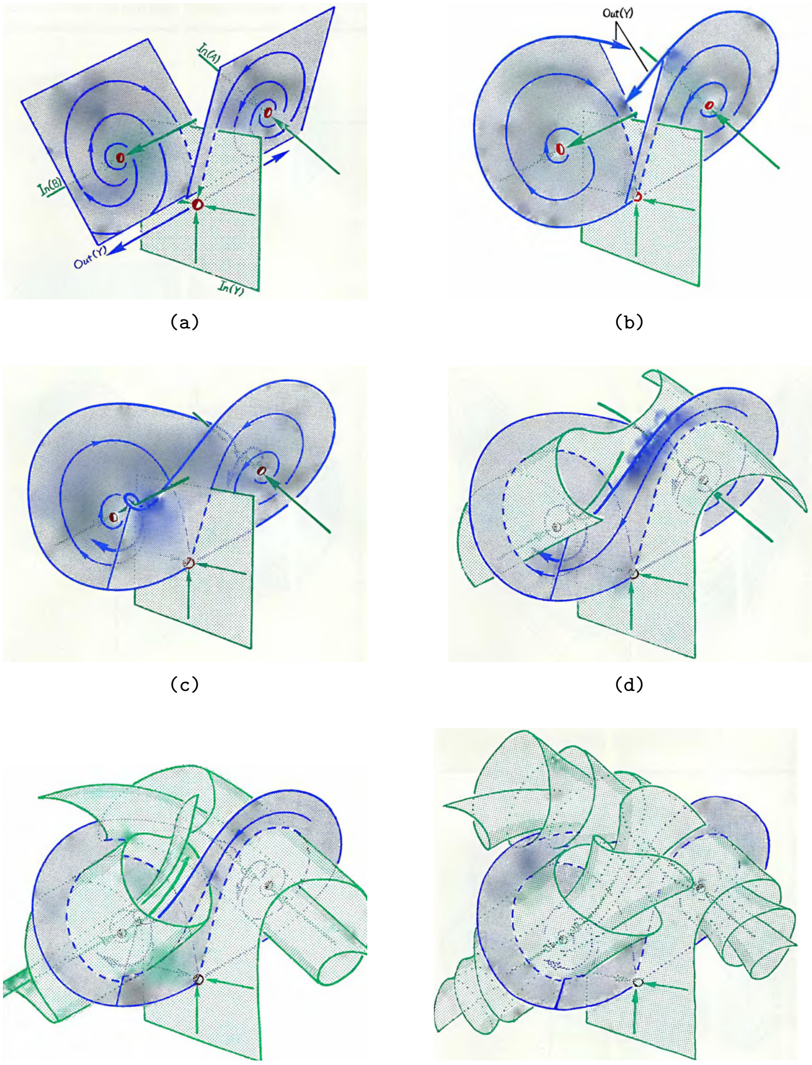
Figure 4.8: Two three dimensional attractors: *Y* saddle attractor with two dimensional *inset* (node), *A* saddle attractor with spiral *outset*. Abraham Shaw *Dynamics - The Geometry of Behavior*, p. 383

disappear as separable elements. In other words, the idea is to create the conditions in which performer and computer music system are enabled to mutually interact such that their joint evolution might result in a coherent and synchronous dynamic evolution.

This mindset, based on a thinking about interaction as a coupling between dynamical systems in phase space, has been put to "test" in the context of small case study, *phase space experiment*. In this case study, a relatively reduced experimental setup has been realised in which a performer is asked to interact with a computer music system (in the following CMS) whose sound output is modulated by the evolution of a simple two dimensional dynamical system (*centre* attractor, the prototype of all harmonic oscillator systems) in turn perturbed and influenced by their playing. The aim of this experiment is to observe:

- If and how the performers' reactions to the sound produced by the CMS are informed by the specific attractor type used in designing the system.
- How salient the behaviour induced by the attractor is for the performer.
- If phase space structures give rise to perceptually clearly distinguishable musical gestures.

Again, it is important to note it is the global behaviour which is relevant. That is: does the behaviour of the whole coupled system composed by the CMS and performer as experienced by an audience, present significant and



(a) (b) (c) (d) (e) (f)

Figure 4.9: The "construction" of the Lorentz attractor by the interaction of 3 different attractors. Abraham Shaw *Dynamics - The Geometry of Behavior*, pp. 384-389

identifying characteristics (evident when the dynamical system implemented in the CMS is varied). If it is, this could point towards an effective employment of the phase space thinking model in the composition of interactive live-electronic environments.

The case study was too small and too reduced to be considered a full-fledged experiment which providing clear scientific insights. Still, going through its implementation and witnessing how two professional musicians (Saxophonist Joel Diegert and Violinist Lorenzo Derinni, see figure C.2) exposed to such kind of interactive environment would react, yielded precious experiences and observations which could be the basis of further investigations in the future.

Both musicians had experience with works including live-electronics to different degrees. They were asked to play, hear and react to the CMS's sound and find their own way to interact with it: they were not given a prior

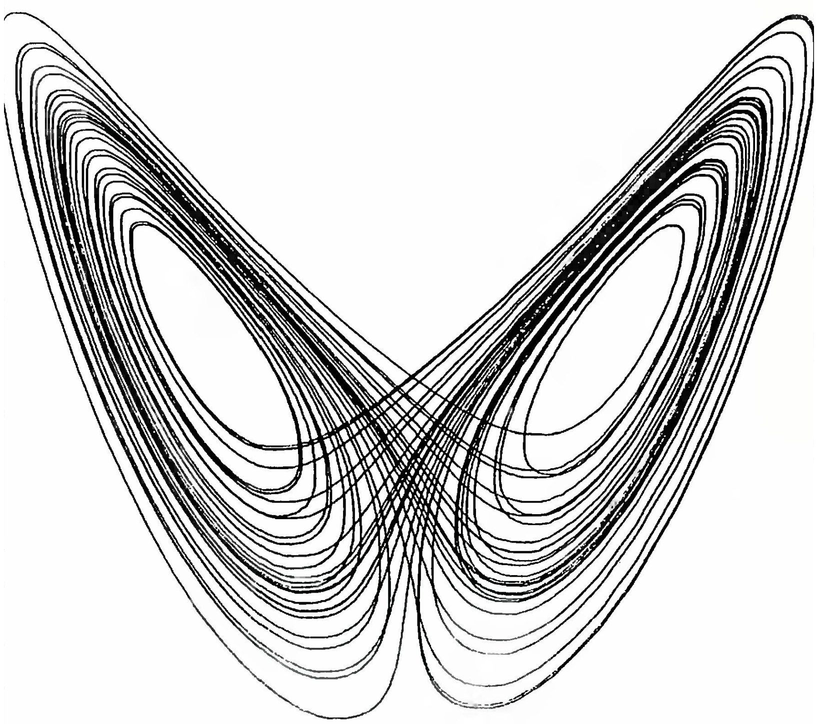


Figure 4.10: The phase portrait of the Lorentz attractor. Abraham Shaw *Dynamics - The Geometry of Behavior*, p. 387

explanation of the system's functioning. Eventually, in informal interviews after the testing sessions both stated that the kind of interaction they had felt had definitely different qualities to what they were accustomed to in previous situations.

- Clearly for both, what they heard coming from the CMS was not only an "effect". That is, it was clear that the interaction could not be simply reduced to a one-way causal relationship where the sound they produced was the only source of activity. The system was perceived as having some kind of own activity.
- Even if the attractor used in the model was very simple, they could no exactly formulate in words this behaviour. But, they clearly felt a sort of own "will" in the CMS, which they could influence at times more or less effectively.
- After some initial adaptation time, they showed some synchronisation to the base system's evolution in their playing: a sign that its behaviour resonated with their perception.
- Both underlined an aspect that was not really clear prior to the test: It is not possible for the performer *not to interact*. There is a sort of continuous "contact" with the CMS; they could not choose to simply "back off" a while.

- They defined the system as very "sensitive"; clearly any kind of movement or sound they produced was reflected in some modification in the CMS's reaction.
- Despite the immediate perception of activity, behaviour and sensitivity, finding a working "interaction mode" is difficult (and maybe frustrating at times), but intriguing.

Especially interesting was the experience while working with violinist Lorenzo Derinni. After some hours of testing a different mind set made its way in his performance. At that point the circularity of the interaction between system and performer became evident in a performing that was playing and listening at the same time. After this experiment, he also reported that at that moment he experienced a *heightened sense* of hearing, of his instrument and of time.

By involving professional musicians in this study we addressed performers highly sensitive to sound and very detailed in producing it. We did not consider however that, even if asked to concentrate only on the sound and ignore more musical approaches for the test, for them these two aspects (sound and musical structures) are non separable. Therefore, for both, the scenario was clearly too "simple" in some way; meaning that they would expect more variation in the system's behaviour.

Further, both asked for more "sensitivity" especially towards small impulsive or rhythmical structures: the implementation of the system used smoothing (low-pass filtering) at various levels of signal conditioning in order to keep it in some more stable region in which the system's evolution would remain bounded. This choices of course limited the sensitivity of the system. In general, they asked for "faster" reactions and actions by the system.

Yet, on these premises, further development and a more extended and systematic study seems to be promising. Suggestions and observations should be taken into account in a future experiment. Also, additional questions and features could be addressed e.g. if and how the affect of qualitatively different attractor types could be observed. The focus should remain also on the qualities and consequences of the coupling: this aspect should be object of a more in-depth study. Questions pertaining to how this coupling and in particular its modulation as part of the dynamical system's agency are surely central, and possibly, in view of the collected experiences, even essential.

5

Conclusions and Outlook

This thesis develops an attitude towards interaction in the context of computer music. The interplay of three elements forms the basis for this work:

- A scientific and theoretical analysis of the concept of interaction and of the understanding thereof in the field computer music in relation with theories of *perception* and *cognition*.
- The mathematical theory of *dynamical systems* and its applications reaching into both computer music and cognitive sciences.
- A direct, personal *aesthetic engagement* in the development of interactive computer music environments and in concrete *artistic experimentation* which puts issues of interactivity at its centre.

Each of these aspects is represented by one of the preceding chapters.

I am aware that these elements, and therefore their chapters, might appear in part thematically far and in some way isolated from each other: the path leading from one chapter to the other might appear a bit broken. To maintain this impression and not smoothing it out, was a conscious decision: contrasts might actually help in bringing out an overall image of interplay. Also, connections pointing across the chapters are provided throughout the text, even if not always fully developed. I will try here to give a concise résumé of the main themes and their connections and then provide a condensed account of the core claims of the thesis.

5.1 Résumé and central claims

Chapter 2 (Interaction) introduces an understanding of computer music in terms of a *generative computer music*: the means provided by the computational medium for formulating and performing processes, are here seen as the essential characterising elements of this form of composition. As praxis and technological development in this context evolve, due to the inherent separation between sound source and interface, questions of performance and *interaction* become more and more central, requiring a clearer understanding thereof. A central assumption of this thesis is that a precondition for this understanding is a clearer insight in human *perception and cognition* as interaction and interactivity is a perceived quality we experience in relating to entities, machines or organisms. The *enactive approach* to cognition provides such an insight: this theory establishes tight links of dynamical exchange between the processes of cognition, action and perception. From this perspective, interaction becomes thus the main mode through which *knowledge* about the world is constructed in the sense of a *mutual influencing* exchange between perceiving agents and their environment. This is the understanding of interaction this work relies on. The theory of *agency*, which is part of the enactive approach, describes which are the qualities an entity should exhibit in order to enter an interactive relationship with a counterpart. A further essential thought is here that, providing a computer music generative process with such qualities, would allow a performer to engage in a mutually interactive relationship.

Chapter 3 introduces *Dynamical Systems* as a mathematical theory which is concerned with the temporal evolution of entities or ensembles of entities under the rules of their mutual interactions. The theory arises from the observation of complex physical phenomena and provides the tools for a qualitative analysis of their temporal behaviour in terms of geometrical structures in *phase space*. The language of dynamical systems can be applied to an extremely wide range of phenomena and is abstract enough to transcend the boundaries of the purely physical world. Dynamical systems afford a *process-based* way of thinking and an *ecological* perspective that looks at the connections and interactions between all of the elements involved in a system rather then isolating them. Hence, this language finds its way into most diverse fields in which those aspects are central, like cognitive sciences and the theory of enaction, but also theories of perception and a specific praxis of computer music. While in most approaches this language is used at a metaphorical level, this thesis attempts to establish an approach which concretely employs the mathematics of dynamical systems in the realisation of interactive computer music environments. A language which formulates and constructs the interdependencies between entities in a system in form of differential equations: through the flow of time, a composition of mutual interactions will emerge.

The practice-based artistic engagement with the issue of interaction in computer music takes a parallel path and is presented in Chapter 4 Case Studies. As interaction is at first understood as bodily involvement, physical models, a subset of dynamical systems, are used for tapping into bodily sensory-motor knowledge of performers. The hypothesis is that by modelling processes with physically inspired models, temporal behaviour can be composed whose qualities resonate with previous gained sensory-motor experiences and with the mechanisms of our perception in general. The software framework *rattle* is the basis for the development of these environments. Both personal exploration and collaborations with performers and dancers in the context of the *Embodied Generative Music* project allow for a continuous exploration and aesthetic experience of interactive environments. This is an essential process in order to make implicit assumptions visible and allow for more precise formulations. Through this experimentation a paradigm of *mutuality* appears in opposition to a *control* or instrument-based approach in which the computer music system is understood as an extension of the performer's body. Interaction with a generative process seems to require reciprocity between performer and system, i.e. the computer music system *appears as agent* with which the performer interacts; it does not disappear as fully embodied instrument. The final case study explores the idea that using the language and formalism of dynamical systems, the computer music system can be provided with the *affordances* of an agent thus allowing for a truly interactive relationship between performer and generative process.

I would highlight the three following, mutually dependent points as central claims:

- *Interaction is the process of continuous mutual influence of two coupled agents.* Interaction is thus a *process* not a state. An ongoing continuous exchange of influences between two agents. The agents are coupled in the sense of a dynamical system: each affects and is at the same time affected by the other in its temporal evolution. Interaction is further *situated*, as it is the result of a process that has to be performed, it is not a condition that can be set *a priori*. To compose interactions means therefore to formulate interdependencies between agents so that a process of interaction might emerge.

- *The language of dynamical systems allows to formulate and analyse processes of change and interaction.* Dynamical systems theory is the mathematical language of *change* and *behaviour*. It enacts a perspective of the world in which temporal processes emerge according to rules of change connecting the entities populating it. These rules of change are *couplings*, they are bi-directional and cyclic connections: change in one entity provokes change in another coupled entity which in turn influences the former. As our perceptual apparatus is especially sensitive towards change, i.e. to the perception of change in form of *derivatives*, dynamical systems provide means for formulating processes whose evolution, their temporal structure or behaviour, resonates with our perceptual structure.

- *Agency is a perceptual quality modelled with dynamical systems*. Enaction theory describes an agent as an entity having *individuality*, *activity* and *adaptivity*. Hence, an agent is a recognisable source of activity in the environment with which it is coupled: as it is adaptable it is further capable of *self-regulating* this coupling. An agent defines itself through the qualities of coupling it exhibits; it appears and can be recognised as such only in the process of interaction. Agency is therefore a temporal perceptual phenomenon. The internal structure of an agent as well as the form of coupling it exhibits can be formulated in terms of dynamical systems.

Agency develops in the course of the dissertation to a central theme. It is the perceptual quality that a generative computer music system should present in order to allow for a mutual interaction with a performer. The generative sound process itself is at the "core" of the agent; it is its individual and active character and is expressed in terms of a dynamical system and thus exposes a perceptible and sensible behaviour. This system's structure, at the same time, connects with its environment and exposes itself to external influences. Agency becomes the *affordance* the generative process offers for being interacted with: it is the quality that allows the process for being "touched", grasped and interacted with: the haptic metaphor is here used following Alva Noë's description of vision as an active process of perception.[1] It is the "surface" the process presents towards the composers/musicians/performers' influence, both *resisting* them as part of its agent's character and offering opportunities for being pushed.

The composition of mutual relationships between the computer music agent's state space and external conditions is the basis for a composition of agency. A composition that will emerge in the process of interaction as a mutual shaping and forming of the space of possible actions.

[1] Alva Noë. *Action in Perception*. The MIT Press, 2004

5.2 Open questions

What are the consequences and effects of this attitude in general and on computer music practice in particular? This question leads into many directions which have not been addressed directly in this work, maybe just suggested. The following are a few of those directions, which should be object of future research.

What does this perspective imply for the composition of interactive computer music? It seems clear that this kind of understanding poses interaction itself at the very core of every piece employing it. If fully acknowledged, such understanding requires the piece to *emerge* from the unfolding of the interaction. A situated process which develops in that moment, on that stage, with that performers etc. Anything else would be in opposition with its enactive roots.

So, where is the piece? It cannot be a score in a traditional notation's sense. The performers cannot have to follow a predetermined path: they have to be put in the conditions to act and react and co-determine the shape of the piece. The piece *is* the unfolding of interaction, it is the evolution of the joint dynamical systems of performer and computer music system. A different notation seems to be required for capturing this situation. But at same time, its seems necessary that performer and composer develop a different kind of thinking.

What is the piece? If everything happens in the moment and is dependent on every aspect of the ecology of the performance, can we speak of a defined "piece" at all? Again, probably not in a traditional sense: a piece consists in the formulation of a situation in which a specific set of processes might emerge. Composition means creating the conditions for the emergence of an interaction process.

A dynamical system perspective requires that all involved entities are put on the same level: all contribute to the system's evolution and are indispensable for its path. That is, composer, musician, computer music system, audience and venue, all share the same system and all have a crucial influence on the performance and therefore on the piece. Traditional hierarchical relationships are therefore to be put into question from this ecological (and political) perspective. How should a piece be framed? Who is the author?

Control paradigms are contrary to this attitude. Couplings between the agents in the systems are always mutual, there is no unidirectional action of one agent over the other. Every entity senses and acts in accordance to its inner structure. The individuality of the agents is always respected: it is the motor of the mutuality. The computer music system has therefore to be carefully liberated from all tendencies of "instrumentalisation" that would possibly transform it into a tool in the hands of the performer. Further, the performer can be liberated from its role of "controller" or "interpreter" and be put in a more active and determining role in the composition. Control in fact, is a circular phenomenon: as cyberneticians have understood, control is dependent on the viewpoint from which the relationship between controlled and controller is seen.[2] From the perspective of the heating mechanisms the thermostat is the controlled entity: the controller has to adapt to the control mechanism like the controlled: the paradigm of control limits the possibilities of both entities equally, controller and controlled. These thoughts were responsible for the birth of second-order cybernetics, which sought a perspective evening the relationships between observed entities. Does the perspective developed in this work imply a kind of "second-order composition"?

[2] Heinz Von Foerster. *Understanding understanding: Essays on cybernetics and cognition*. Springer Science & Business Media, 2007

Questions regarding the consequences of a thinking based on an essentially *circular* concept of relations should be addressed. A circularity that appears strongly connected with an (at the moment) implicit assumption posing that the *temporal dimension* of things is essential for their existing. An interesting direction to pursue seems here the philosophy of Alfred N. Whitehead, which currently experiences a growing interest, as a consequence of the work of Luciana Parisi on the status of the algorithm in generative art.[3]

[3] Alfred North Whitehead, David Ray Griffin, and Donald W Sherburne. *Process and reality: An essay in cosmology*. University Press Cambridge, 1929; and Luciana Parisi. *Contagious architecture: computation, aesthetics, and space*. MIT Press, Cambridge, MA, 2013

Most importantly, I think that this dissertation shows the need for an inquiry in the *specificity of computer music*. It seems to me clear now how paradigms of "traditional" musical praxis have been more or less "blindly" applied to the field of computer music. This is of course in itself a reasonable approach: those paradigms have worked well until now, why should they not work for computer music? Still, I do believe that computer music affords a qualitatively different approach, way of thinking and praxis in particular due to its essential generative character. These aspects are still not fully acknowledged. Concepts of instrument or control, composition as a static "object", a solution to a "problem", are in my opinion in opposition with the process-based way of thinking at the core of generative music. Hence, I would call for a *radicalisation* of the concept and definition of computer music: a clear formulation of its core qualities also with the intent of marking a difference or defining a separating boundary with traditional musical praxis: not in the sense of an insurmountable trench, but rather as a rhetorical tool for eliciting new modes of thinking.

5.3 Future Directions

In this last section, I would like to report about the planned or already ongoing research projects or case studies in which this work's research questions are pushed further.

5.3.1 Phase Space thinking: experimental explorations

The case study Phase Space Thinking: an experiment reported in 4.3.1, was a valuable process for this dissertation. Conceiving the experiment and carrying it out, even if in such a small scale, contributed greatly to the sharpening of questions and concepts. The necessity to conceive and realise an experimental setup which exposes the test persons to the right "questions" drives a process of reduction of those questions. The simplest and most essential formulation of the problem is the key to a successful experiment and is simultaneously already of great scientific value. Furthermore, some aspects of a phenomenon can only be seen through a systematic exploration. Therefore, a continuation of this explorations would be an important factor in further research.

In particular, the next phase of experiments should focus on the sharpening of a description of the qualities of coupling function between the agent's internal dynamical systems and external input. That is, how input energy is "digested" by the system without a continuous accumulation which might lead to instability and a too strong suppression which might result in a suppression of the agent's own activity and therefore identity. There is therefore a trade-off between these possibilities which has to be carefully evaluated and described as it has critical consequences.

A further theme which needs attention is the *adaptivity* character of the agent. I think that especially a clarification of this aspect and a formulation in terms of dynamical systems might lead towards a very useful approach in realising interactive environments in general. As Agostino Di Scipio already noted, the key to true mutual interaction is the *self-observing* character of systems, which is tightly related to their adaptivity.[4]

[4] Agostino Di Scipio. 'Sound is the interface': from interactive to ecosystemic signal processing. *Organised Sound*, 8(3):269-277, 2003

5.3.2 *Agency and the* Algorithms That Matter *Project*

Algorithms That Matter is an artistic research project funded by the Austrian Science Fund (FWF, PEEK AR 403-GBL) and led by my colleague Hanns Holger Rutz and myself. The project takes on the questions of agency in the context of computer music praxis and is thus tightly related to this dissertation.

The basic assumption is that computational processes, algorithms, possess an inherent agency as an irreducible and defining quality. This agency is perceivable in the actual execution of the algorithm, the unfolding of the computational process and the traces it produces and in the very process of constructing or "building" algorithms.

The project ask questions about the medium-specificity of computation, in contrast to approach which employ the computer mainly just as a tool to solve well-defined problems through the execution of programmes. Algorithms in fact, have traditionally been understood - in computer science, music and art - as a formalisation of thought; similar to ideas they were seen as immaterial and timeless. For instance, early algorithmic composition practices fall into this characterisation: in the words of Gottfried Michael Koenig, the computer is concerned with finding the solution to the problem "given the rules, find the music"[5].

[5] Gottfried Michael Koenig. Kompositionsprozesse. In *Ästhetische Praxis*, volume 3 of *Texte zur Musik*, pages 191-210. PFAU Verlag, Saarbrücken, 1993

In contrast, the *Algorithms that Matter* project picks up impulses coming from current cultural studies and philosophy which suggest that such praxis is characterised by two *entanglements*, first between the human and the apparatuses of creation (e.g. computers, software, algorithms, experimental arrangements, materials), and second between apparatuses and the objects produced (the arrangements and processes vs. the pieces of music or artistic knowledge). The concept of entanglement is borrowed from Karen Barad's work and means that two sides do not exist prior to their interactions, their separation happens only analytically.[6] These entanglements form the starting point of the project *Algorithms that Matter*.

[6] Karen Barad. *Meeting the universe halfway: Quantum physics and the entanglement of matter and meaning*. Duke University Press, Durham & London, 2007

Algorithms are taken as the crystallisation point of an inseparable human-machine agency in computer-based composition. Thus algorithms are studied as *performing entities* that emerge from specific artistic practices. And vice versa, the project is interested especially in how these practices are transformed by the agency of algorithms. While existing research often focuses on the refinement of algorithms, machine learning systems, etc., *Algorithms that Matter* looks at the process through which the algorithms and codes have come into existence.

The central question of the project thus is:

> *How do algorithmic processes in experimental computer music structure artistic praxis and the understanding of composition and performance?*

In other words, the hypothesis is that these processes can unfold a specific *agency* that retroacts and changes the compositional praxis becoming a new organising principle.

In addressing this question, the *Algorithms that Matter* project builds upon a new understanding of algorithms as entities bearing a material *performative* aspect that exceeds their design. An excess that, for instance, becomes material when algorithms have unintended consequences, crash machines, etc.

Luciana Parisi's work serves as a basis for this perspective.[7] In Parisi's theory, an algorithmic object not only possess a finite material form, its particular implementation and set of instructions. It is complemented by an abstract reality that makes it possible to produce and transform novel data. This surplus value is non-written and non-implemented, *in-compressible* in the sense that it cannot be formulated. Through a *material engagement* which oscillates between these two perspectives, the experimenting with and the observing of algorithms, the project aims at constructing an experimental system in which compositional practices serve as an epistemic tool in exploring the algorithms' performative essence.

[7] Luciana Parisi. *Contagious architecture: computation, aesthetics, and space.* MIT Press, Cambridge, MA, 2013

In the project, research questions are concretely addressed through principles of iterative experimentation. The approach to observing processes is inspired by Karen Barad's concept of "diffractive reading" which describes "an iterative (re)configuring of patterns of differentiating-entangling".[8] That is, through a series of connected, but diverse *re-configurations*, we attempt to observe the boundaries drawn by the agency of algorithms which may lie transversal to presumed boundaries such as a specific piece, performance, composer, format etc.

[8] Karen Barad. *Meeting the universe halfway: Quantum physics and the entanglement of matter and meaning.* Duke University Press, Durham & London, 2007

The project is thus divided into four subsequent "configurations". Each configuration brings together a group of artists and researchers who, over a period of two months, develop a series of algorithmically related sound pieces. The process is observed and transcribed into multiple forms of presentation and discourse and a continuous online exposition is complemented by distinct gatherings and symposia. Each group consists of three persons: the two principal investigators, Hanns Holger Rutz and David Pirrò, and one additional artist/researcher. This will be an invited person in order to ensure a greater level of effectiveness and validity reaching beyond the individual experience of the main investigators. In pursuing the investigation, one host environment in which algorithms are implemented and run will be used by all researchers in each configuration: this framework forms part of the laboratory apparatus. There are two software systems which will be alternatively used to this end: *Sound Processes*, maintained by Hanns Hogler Rutz and *rattle* (David Pirrò).

The research project is hosted at the Institute of Electronic Music and Acoustics (IEM) which is part of the University of Music and Performing Arts Graz (KUG) for a total running time of three years from 2017 to 2020.

A
A catalogue of works

This chapter contains a *catalogue* of selected artistic works and studies which are tied to this dissertation, either on the level of the tools used or the aesthetic experiences addressed. On the one hand, these works both served as a test and use case for the technical and conceptual framework. On the other hand, the process of developing and staging those works allowed observations, which otherwise would have not been possible. In this sense, I regard these works as *experimental*, in the original meaning of the term. Trials, or tentative procedures; acts of testing a principle or a supposition; operations staged for the purpose of revealing something unknown.

These works have been developed, staged or performed embedded in some of the artistic research projects I've been part of. Also, my artistic practice plays an important role here, as it is intertwined with those research activities.

A.1 Bodyscapes

Some of the paragraphs in the following section are based on parts of the paper "On artistic research in the context of the project embodied generative music" by Gerhard Eckel and David Pirrò, which appeared in the Proceedings of the ICMC 2009

Bodyscapes is an interdisciplinary piece at the intersection between dance and computer music. It has been realised in a collaborative artistic research process by Valentina Moar (dance, improvisation and choreography), Gerhard Eckel and myself (composition, live electronics, interaction design and software development) in a total of 7 days during two working periods in December 2008 and January 2009. The collective research and creation work was carried out in the context if the *Embodied Generative Music* project at the IEM in the *aesthetic laboratory* (see The *Embodied Generative Music* Project), where the piece was also premiered on January 20th. A documentation video of the premiere is available online[1].

After a prolonged period of development and experimentation carried out within the *EGM* project exploring different motion-to-sound mappings with various dencers, we felt the need to condensate our findings and observations in a short piece which then became *Bodyscapes*. Therefore, the piece consists of different scenarios, i.e. *bodyscapes*, which enact a particular relationship between bodily movement and sound, each baring a recognisable characteristic and an aesthetic identity. Each scenario revolves around a specific artistic idea or a metaphor, which serves as the basis for the development of the sound model and its mapping to the dancers' movement that in turn induces a particular dynamics in their movement as a consequence of the behaviour exhibited by the resulting sound.

The following section describes the four bodyscapes appearing in the piece: they are named after the main metaphor driving their conception.

- *The Persona*: Starting our inquiry, we decided to concentrate our investigation on the dynamics of bodily movement. Thus we searched for the most basic metaphors and sonic images connected to body dynamics. We were seeking ideas connecting body dynamics and sound while making these relations clearly readable for the audience and "wearable" by the performer.

  We identified the following characteristics this bodyscape should incorporate:

  1. directness of the link between movement and sound
  2. simplicity of the relation,
  3. clearly readable causality of sound dynamics.

  As the body is always moving within air, the sound created by such movement inspired the sound model we used in this bodyscape, which simply consists in lowpass-filtered noise where the cutoff frequency of the filter is mapped to the speed of the movement. Our idea also implies that sound should only be produced if there is movement at all - one of the clearest and most readable mappings of body dynamics to sound - so we extended the mapping such that the speed also controls the volume.

  In this bodyscape we take into account the spatial position of every joint in the body of the dancer, computing the speed of each and using the fastest at any moment in the mapping. This is motivated by the assumption that the attention of the audience is shifting following the fastest body part - thus the sound dynamics follows the visual focus.

[1] https://vimeo.com/4949316: accessed 19/07/2017

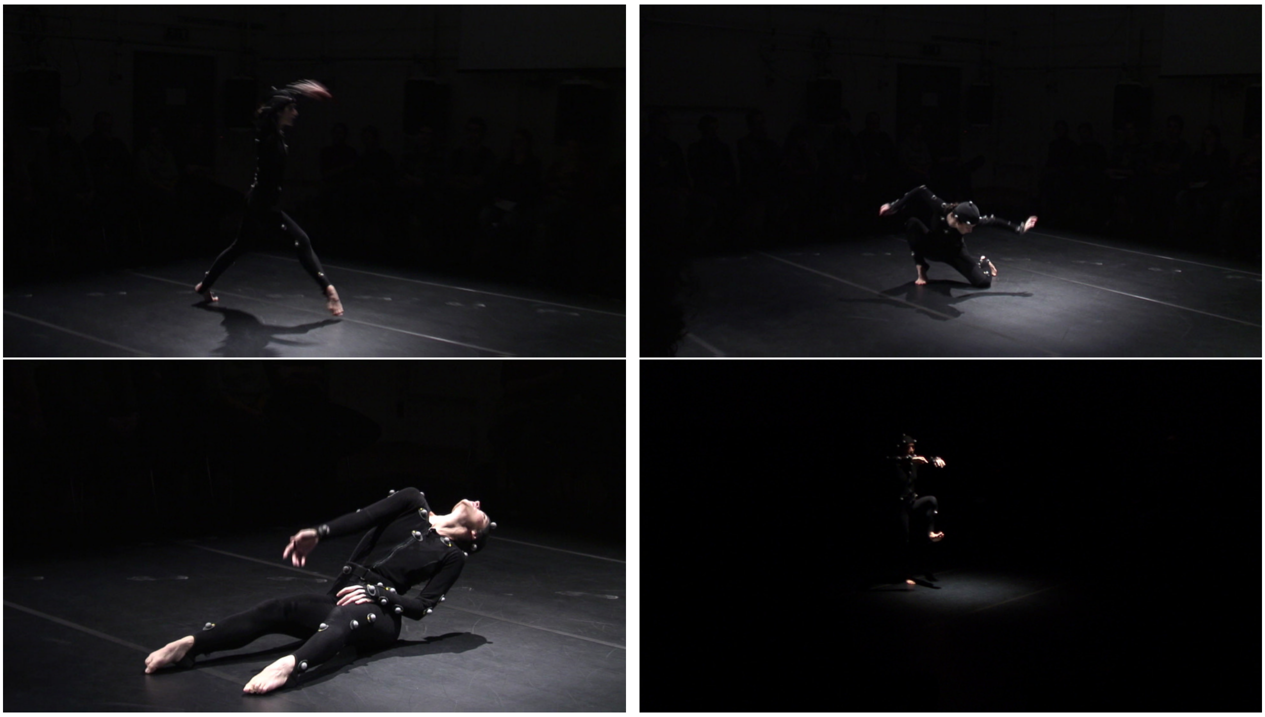


Figure A.1: Four moments of the *Bodyscapes* performance in the CUBE at the IEM. Referring to the explanations in the text, from top left the *persona*, the *partner*, the *frame* and the *object* on the bottom right.

The details of the mapping were determined empirically in experimental sessions preceding the production phase. The precise aim of these sessions was to establish a mapping faithfully portraying the *effort* involved in carrying out the movement. A dancers judgment on the aptness of the sonic feedback was used as criterion in the process. The mapping thus found relates the square root of the speed to the logarithm of the filter's cutoff frequency.

In order to keep the focus on the dancer, we have to avoid creating another focus through a localized sound source (e.g. a single loudspeaker). Therefore we drive the hemispherical array of the 24 loudspeakers in our performance venue with 24 de-correlated filtered noise sources sharing the same cutoff frequency and amplitude mapping. This makes sure that the dancing body remains in the center of attention in this bodyscape.

- *The Partner*: Moving away from the directness we achieved with the "persona" bodyscape, we tried to imagine a situation where sound and body were not so closely linked - and could thus engage in a dialog - but the sound was still entirely caused by the performer. We imagined the following basic qualities of this bodyscape:

  1. indirectness of the relation between movement and sound

2. loss of complete control by the performer
3. possibility for the dancer to establish a dialog with the sound produced.

The sound used in this bodyscape is produced by granulation of recorded sound material arranged in two sequences in which voiced and unvoiced vocal sound fragments are separated by silent passages. Vocal sounds have been chosen since they hint the presence of a dialog partner. The material was selected and arranged together with the dancer. The time axes of the two sequences are identified with the two axes of the horizontal plane of the tracking volume (the stage), mapping the time in each sound sequence to the position along one of the axes. The position of each hand of the performer on these axes functions as an index in the sound sequence and determines which part is reproduced through periodic granulation (a kind of "sound scrubbing"). The resulting two signals are then dynamically delayed with the delay time mapped to the square root of the speed of the corresponding hand. The maximum delay of $2.5s$ is reached when the hand does not move and no delay occurs at maximum speed. The variable delay produces a increase in pitch of the reproduced sound material whenever the hand accelerates and a decrease when it slows down. The details of the mapping (maximum delay time, smoothing of the speed) were defined together with the dancer in a process in which she improvised and tested different settings. The two signals are discretely projected from four loudspeakers placed at the corners of the performing space thus being clearly localizable and giving the dancer as well as the audience the possibility to relate to the resulting voices in a "theatrical" way.

- *The Frame*: The performance of the dancer unfolds in a space that in itself is neutral, but that constitutes the frame in which bodily movement can take place. It is not the geometrical space we want to address in this bodyscape but rather the environment, a fixed and not modifiable or controllable context through which the dancer is moving. We then to formulate some basic characteristics of this bodyscape:

1. the relation between movement and sound should be rather felt than clearly readable
2. unpredictability for the performer
3. neutrality of the sound produced.

In this bodyscape we adopted a similar sound model as in the "*partner* bodyscape, using granular resynthesis of a previously prepared sound file. The material used here is constituted of a selection of recorded impulsive and explosive sounds that are produced when heating a pot with a wet bottom on a boiling plate. We used eight sound generators that correspond to the eight joints in the body of the performer that were considered: left and right hands, elbows, feet and knees. The positions of each of these points along one of the two axes in the horizontal plane are used to find the position in the sound file that will be reproduced through periodic granulation.

In this bodyscape we wanted to design an environment that surrounds the dancer like a diffuse atmosphere in which she is moving. Therefore we arranged the short impulsive sounds in a very dense distribution covering all of the tracking space so that the dancer cannot really control the production of single sounds. Thus the performer moving in the space, generates a sort of cloud, as if she was hitting small dust particles in an empty space and we would hear the trace she leaves. Actually, the speed of the movement determines the density of the sound events projected so that the relation between movement and sound is more evident when moving slowly.

The sound in this bodyscape is very neutral, filling indifferently and homogeneously the whole space and it is projected into the performing space from an array of 48 small loudspeakers hung from the ceiling.

- *The Object*: Whereas the *partner* bodyscape allows for a dialog with a kind of an animated counterpart, the *object* bodyscape creates a situation where the dancer interacts with an inanimate object positioned at a particular location in space (the center of the stage). In this bodyscape we wanted to explore the possibility of interacting with sound only through the change of position of the dancers body. The basic ideas for this bodyscape could be summarized as:

  1. clear spatial structure
  2. complete control of sound production for the performer
  3. directness and simplicity of position/sound relation.

  The sound model of this bodyscape distinguishes three zones: inside the object, outside of the object, and on the surface of the object. We found that especially the latter plays an important role in the clear identification of the zones. The perception of the surface is strongly linked to the sense of touch and therefore we payed much attention to the sound design in this region.

The joints taken into account in this bodyscape are – as in the previous one – the left and right hands, elbows, feet and knees. This time we used noise passed through a comb filter with long feedback, thus generating clearly pitched tones. Whenever one of these joints enter a cylindrical region of 1 meter radius placed in the center of the stage, an ADSR envelope is triggered and remains open until the joint leaves this region. Out of this region there is no sound produced. In this way we represent even clearer the subdivision of the space through the presence or absence of sound. The envelope has a sharp attack in order to augment the feeling of touching / passing through a surface. When the dancer is in the region previously defined, the pitch of the generated tones is varied slightly in a range from 3.2 to 4.5kHz according to the distance of each of the considered joints to the pelvis, which in this bodyscape represents the body center.

Such setup clearly defines an "*object*" that is external to the performer, something she cannot move or modify, but is something she can interact with, by moving through and being in.

The development of the movement-to-sound mappings and the calibration of the details of their parametrisations, followed in practice an empirical process which can be described as a classical trial-and-error process shaped and guided by the aesthetic experiences of the involved dancers and composers. One of the main accomplishments of the *EGM* project was the development and the formulation of this *method* by which we tried to gain access to dance performers' implicit bodily knowledge about the aptness of movement/sound relationships. By composing virtual instruments in the framework of the EGM ÆLab allowing to realize particular body/sound relationships, we manage to render certain aspects of this knowledge explicit through sound. The collaborative composition of such a mapping is a tedious empirical process paved with failures and frustrations. This process has met its objective only once the result *feels right* for the dancer (and the observer). Once the sound generation is felt to be embodied and the dancers can fully engage with the sound, they report a heightened awareness of the details of their movement, which also opens new possibilities for the choreographic work as structural aspects suddenly become audible.

After the first working period in the *Bodyscapes* production, dancer and choreographer Valentina Moar explained her experiences in an email in the following way: "*after a while it seems to me there is no more difference between* *the sounds and my skin.*" We take that as a clear indication for having reached a high degree of embodiment in the sound generation with the virtual instruments we are building in EGM. The symbiosis of movement and sound experienced by the dancers is the basis for the choreographic and compositional work. It is also a prerequisite for the special body/sound relationship to be performed and made accessible to an audience.

A.2 *cornerghostaxis#1*

Some of the paragraphs in the following section are based on parts of the paper "Physical modelling enabling enaction: an example", by David Pirrò and Gerhard Eckel, which appeared in the Proceedings of the International Conference on New Interfaces for Musical Expression 2011

cornerghostaxis#1 is an artistic work, a composition for solo bassoon and live-electronics which employs physical models in the design of the interaction between the performer and the electronics. The piece has been premiered during IMPULS Academy 2009 in the context of the Motion-Enabled Live-Electronics workshop at the CUBE of IEM Graz, (bassonist: Dana Jessen). It is the result of the collaborative effort of a team of three people: Stephanie Hupperich (bassoon), Gerriet K. Sharma (composition) and David Pirrò (physical modelling / interaction design).

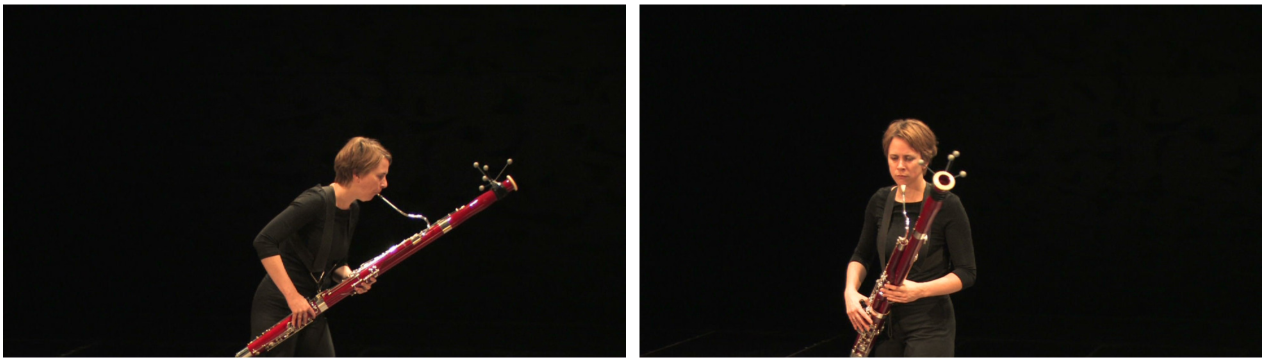


Figure A.2: Two moments of the performance of *cornerghostaxis#1* by Stephanie Hupperich.

The idea of the composition is to put the performer in a dialectical relationship with four electronic sound sources that are dynamically spatialised on a loudspeaker array. This is accomplished by a physical model establishing a gestural and bodily connection between the four channels of an electroacoustic composition and the sounds the performer plays on her instrument and her movements in space.

In the composition the position and orientation of the tracked instrument is used as input for the physical model. The virtual space in which the physical simulation is taking place is a representation of the real space in which the performance took place including the positions of the loudspeakers and the instrument. The physical objects that move and interact in this space are constrained on the surface of a hemisphere on which also the loudspeakers are placed, corresponding to their actual positions.

The objects involved in the physical simulation have a very clear relationship: one can imagine them as electrically charged masses with the same charge. That is, the forces acting between the objects are repulsive[2]. The tracking data is used to control the position and orientation of a square with four "charged" masses placed at its corners. The other masses are free to move on the hemisphere spanned by the loudspeakers: they are also "charged" and repelled by the previous ones as well as from one another (refer to figure A.3). The distances of these masses to the virtual loudspeakers are used to control a simplified DBAP algorithm (for a description of the algorithm see DBAP and ADBAP) that determines how the four channels of the tape composition by Gerriet K. Sharma are spatialised on the physical loudspeaker array. Furthermore, the amplitude of the four sources is slightly modulated according to the movement speed of these masses and depending on the distance to the performer. If the performer is close to one of them (i.e. she "captured" one, see below) that source gets louder[3].

[2] A short video of the model's simulation is available at http://pirro.mur.at/nime11/CGA-Model.mov (accessed 22/07/2017)

[3] A documentation video of the performance at Mumuth Graz is available at http://pirro.mur.at/nime11/CGA.mp4 (accessed 22/07/2017)

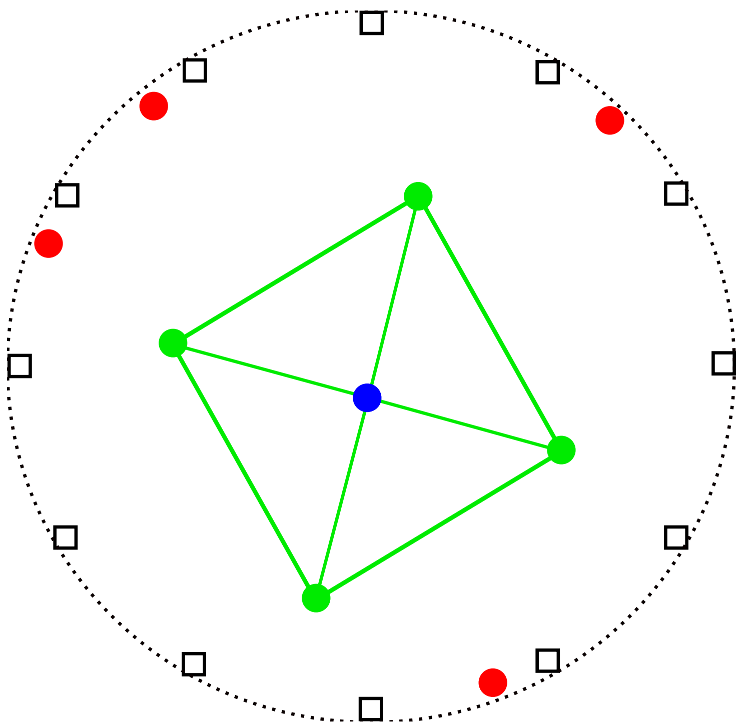


Figure A.3: Graphical depiction of the *cornerghostaxis#1* physical modelling environment. The red masses are free to move but bound inside the disc whose border is the dashed line. These masses interact with each other with an electric-type repulsive force, as if they would be particles with the same electrical charge. They represent the spatialised position of the four channels of the electroacoustic composition on the loudspeaker array (the loudspeakers are the empty boxes at the boundary). The green square is centered on the blue mass whose position and orientation is controlled by the tracked bassoon. The four masses fixed at its corners also exert electric-like repulsive forces on the red masses.

The piece has been conceived as a whole, that is none is its different aspects (e.g. interaction design, electroacoustic composition or the bassonist performance) overpowered the others and the development of each part advanced in parallel to the others. The physical model is not just an effect used to spatialise the tape composition: it is part of the piece, part of the environment in which the composition unfolds.

In the next section we try to summarize how the approach described before in section 2 reshaped the working routine in the explorations and rehearsals of the piece, with respect to our aims. We therefore collect the most important observations being made by the performers and by us. But we also attempt to condense our reflections based on our own aesthetic experiences gathered throughout the process leading to the realization of the piece. We understand the whole realisation of the piece, beginning with the design of the physical model, passing on to the preliminary explorations with the performer, to the rehearsals and the final performance, as part of an experimentation aimed at putting into practice the strategy we described and observe what and how it "happens". An interpretation or evaluation of these observations is not explicitly given, but will be the object of future research.

The most important feedback came from the performers who played the piece. The musicians involved underlined that they felt having achieved a clear understanding of the dynamics of the sound spatialisation and how they could influence it. They could quickly establish an intimate control of the interface / model and they could rapidly learn how to play it.

This understanding also changed the communication between musician, composer and programmer. Relying on the physical metaphor, on which the programming and the whole realization of the piece are based, the performers could more easily communicate with the composer and programmer. In this sense the physical modeling layer appears as a platform for the exchange and refinement of ideas which are shared among all the participants, regardless of their technical knowledge. For example asking "Could you make the masses heavier?" is straightforward for the performer. At the same time it is easy for the programmer to understand and, knowing the model, to accomplish. This is one of the main reasons the performers were actively involved in the development of the piece.

Basically, in performing the piece the musician and the masses play a "hide-and-seek" game. The sources try to escape the performer, always placing themselves at the points most distant to her. This dynamic became very quickly clear to the performer in the first experimental session and her instinctive reaction was trying to find ways of stopping their continuous slipping, blocking one of them by pinning it down, "capturing" it. Also during the performance, the aim for the performer is to "catch" one precise mass out of the four, at a specific moment of the score. But the sound sources, which represent the mass positions in the model, seem to have their own will and try to hinder the musician to achieve her goal, to "win" the game.

It is important to note here that understanding the rules of the play means to understand the laws on which the physical model is based, which are coherently and continuously followed by the simulation and which are inscribed in the sounds' positions and movements. In our experience this gaming quality greatly contributes in making the interaction more clear, interesting and engaging. The reactions of the model are complex but retain a certain predictability. Thus the performer does not have the perception of erratic reactions of the model, which would destroy the illusion of a coherent environment. However the model and the sources are very difficult to control. It is tough to achieve exactly what the composer or the performer wants. The model "resists" at any moment the performer's actions, at the same time offering great detail in interaction, as every little position or rotation change has audible consequences.

In our observations the resistance of the model coupled with the refinement of control, greatly enhances the felt embodiment. As a matter of fact, the musicians, after a short time of experimenting with the model, feeling challenged, asked for a more difficult setup, which was initially kept simple. That meant more resistance of the environment to their actions, but also more detail for their control. Resistance and detail of control create a continuous tension between performer and model that can be seen and felt clearly. This tension captures attention and causes engagement for the musician as well as for the audience assisting at the performance.

The performer could thus fully engage in the play with the environment and with the piece itself. The consistency of the interaction qualities and the resulting sonic feedback, caused a "suspension of disbelief" for the performer, who could truly and bodily trust the coherence of the model's responses, of the connection between her movements and the reactions of the sources. This link was so clear to one bassoonist that she started giving them a "body", regarding them (in her own words) as "colleagues", like she would do with other human players in an ensemble. Furthermore she reported an enhanced sensibility not only in the perception of the spatial location of sound, but also of her own movements, her position in space as well as an increase of her proprioception.

I underline at this point that the model was neither visible to the audience nor to the performer, neither during the rehearsals nor the concerts. It was not clear to the viewer how the model works or exactly which forces were acting in the simulation, as this was not explained before the concerts. It was not my aim to make this aspect evident. In our approach the physical modeling layer is not intended to be clearly perceivable as such, but its purpose is to enhance the enactivity of the interaction.

Nonetheless, during the informal discussions that took place after the performances, it appeared that the relationship between movement and sound, between action and spatialisation, between the player's sounds and the electronic sounds was clear also to the audience attending the performances. The player's efforts, inscribed in the qualities of her playing as well as in her body could be seen and could be conveyed to the spectator.

A.3 Tball

Some of the paragraphs in the following section are based on parts of the paper "Motion-Enabled Live Electronics by Gerhard Eckel and David Pirrò, which appeared in the Proceedings of the Sound and Music Computing International Conference, SMC 2009

Similarly to *cornerghostaxis#1* (see previous section cornerghostaxis#1), the piece *Tball* for trumpet and live-electronics is a composed environment in which the musician and performer participates in a real-time physical simulation. The simulation establishes a relationship of interaction between the tracked performer, his movements and gestures in space as well as the sounds he produces and the spatialised movements of a sound source moving in the space. *Tball* has been developed in collaboration with musician Paul Hübner and performed during the *Motion Enabled Live-Electronics* (*MELE*) Workshop that took place at IEM in the context of the Impuls 2009 Festival and Academy in Graz[4].

This composition's environment is thus inhabited by two agents: the trumpet player and performer and a moving invisible ("virtual") sound object, the *Tball*. As in *cornerghostaxis#1* the virtual space in which the simulation takes place is a representation of the performance space, including the loudspeaker positions, the floor and the position of the bell of the tracked trumpet (see figure A.4). The spatial movement of the *Tball* has been modelled

[4] A documentation video of the performance can be found here: http://pirro.mur.at/Tball/MELE_tball.mp4 (accessed 22/07/2017)

Figure A.4: Two moments of the performance of *Tball* by Paul Hübner.

according to a simple spring-mass physical model. It is a point-like object attached with a spring to the a point at the centre of the stage around 1.8m above the floor: thus, once set into motion, it will oscillate with a given frequency according to its mass around its anchor point, possibly hitting the floor, where it will bounce off. The position on stage and the orientation of the tracked trumpet are linked to the position of the second object in the simulation (refer to figure A.5)[5]. This object (marked as the blue filled ellipse in the previous figure A.5) can be imagined as an "prolongation" of the trumpet from the bell's position in direction of its orientation: when the performer produces a sound with his instrument, this object exerts a strong attractive force on the *Tball* (with an intensity much greater then the force the ball is bound to the center of stage). In effect, whenever a sound is produced with the trumpet, this object "grabs" the *Tball*. Additionally, this force is scaled by the relative angle of the *Tball* and the trumpet's direction: that means that this "grabbing" force has full effect when the *Tball* is exactly in the direction of the playing trumpet whereas it is minimal (or even zero) when the *Tball* is on one side of the trumpet (e.g. at 90 degrees with respect) to the trumpet's direction. The grabbing force stays on as long a sound is produced on the trumpet and is switched off when there is no sound.

The *Tball's* sound is spatialised on the loudspeaker array of the IEM CUBE according to its position relative to the loudspeakers in the model using a the *ADBAP* algorithm introduced in DBAP and ADBAP. That is, by listening to the sound from the loudspeakers and its dynamics, the behaviour of its change, the performer can hear where the *Tball* is. He then can engage in a sort of catch and

[5] A short video of the model's simulation can be found here: http://pirro.mur.at/Tball/Tball_Model.mov (accessed 22/07/2017). The black dots represent the loudspeaker positions, the moving green point the trumpet's bell and the red point the *Tball*.

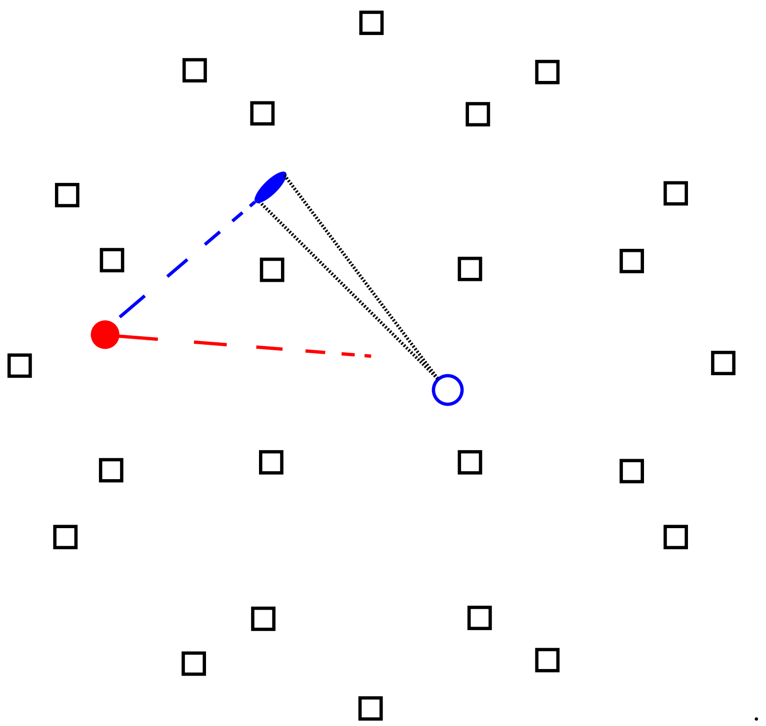


Figure A.5: Top view of the *Tball* environment. The red point represents the *Tball* object, which is attached with spring to the center of the stage (the red dashed line). The blue squashed disc represents the prolongation point of the trumpet bell, starting at the tracked bell's position (empty blue circle). This objects also exerts a force in the simulation (the dashed blue line) on the *Tball* which, whenever the trumpet produces a sound, "grabbing" the *Tball*. The empty black boxes represent the positions of the 24 loudspeakers in the IEM CUBE (organised in 3 rings) on on which the *Tball* sound source is spatialised

launch game, grabbing the ball and launching it away or against the floor.

During the whole performance the sounds played by the musician are continuously recorded into a ring buffer of fixed length: this recording is the basis of the sound the *Tball* produces. As new input are added into the buffer, this sound becomes more and more dense as the performance goes on: accordingly, as the *Tball* "stores" all this sounds, its get bigger and heavier, making it more and more difficult for the performer to grab and control it. The performance ends when eventually the ball "explodes" like a balloon that has been inflated too much.

During the composition of the piece, the work with the instrumentalist and his input have been of great importance for implementing a well balanced environment that allows for a high degree of embodiment. Further, even if only small time slots where at our disposal for rehearsals, the performer could quickly construct a detailed image of the environment's dynamics, that resulted in a high degree of control. Surprisingly, in spite of never having seen the graphical representation of the running simulation, the performer even asked for a more "difficult" parametrisation of the "grabbing" force: in fact, initially the angular range at which the force could act effectively has been left quite broad as the performer could rely exclusively on his hearing in order to locate the moving sound source. Apparently the dynamics and the behaviour inscribed in the sound source's movement in space is a clearer cue than expected for the performer, allowing him to "predict" quite precisely the object's location in a way extrapolating from its past path, that after a short period of time this became even "too easy". We ended up by narrowing the angle range, thus requiring a better alignment of the trumpet with the object for the grabbing force to be effective.

Eventually, the trumpet player and performer could engage in a play with the *Tball* and by listening to the sound resulting from the interaction and watching the behaviour of the instrumentalist, the object could appear also in the audience's imagination.

A.4 Interstices

Some of the paragraphs appearing in the following section are based on parts of the paper "Exploring sound and spatialization design on speaker arrays using physical modelling" by Georgios Marentakis and David Pirrò, which appeared in the Proceedings of the 9th Sound and Music Computing Conference, SMC 2012

Interstices is a multi-channel sound installation which I realised in cooperation with colleague Georgios Marentakis and that was exhibited in the *ESC medien kunst labor* in January 2012.

The installation is an investigation into the spatial appearance of sound projected by a non-standard[6] speaker distributions. More precisely, it is an *artistic exploration* of how the composed temporal organisation on different time scales of synthesised sound, i.e. the *behaviour* it exposes on multiple levels, affects its perceptual spatial appearance.

[6] *Non-standard* here refers to loudspeaker distributions which are not reducible to the spatial arrangements required by standard spatialisation techniques.

At origin this work, is the hypothesis that the shape of the composed temporal evolution of a sound is a strong cue, possibly even stronger than expected, that strongly contributes the construction of a coherent perceptual sonic image. Most "standard" algorithms that relate or "transpose" sound sources into space, depart from a static conception of sound sources, ignoring movement or dynamical qualities. This is in some way understandable, as the effects of sound source movement on localisation have not yet been sufficiently studied and formulated, mostly because of the lack of sufficiently advanced speaker array systems that would allow a systematic investigation of these aspect. However, it is known that for instance head movements, clearly contribute to localisation. Even if the relevance of this cue cannot be clearly stated at the present time, it seems therefore plausible to presuppose that dynamic qualities of sound including, but not limited to, its location, could play and important role in perception.

The work naturally relates to the general theme of sound spatialisation in electronic music, but, grounding on the former perspective, it tends to abandon the tendency to conceive sources as perfect points without extent and attempts to generate sounding "geometries" emerging through a consistent behaviour inscribed in their dynamic evolution. *rattle* served here as the framework to formulate and compose such behaviour on different scales within time and space.

Here, the particle-based physical modelling and simulating version of *rattle* was used: systems of particles connected together in a network, linked by variable forces acting between them was the general formulation I used. The behaviour of each of those objects and eventually of the whole compound is determined by the form of the interactions, i.e. the form of the forces acting between them. Defining and possibly changing those means to compose and alter the dynamics on the level of the single objects and on the level of the whole network compound: one actor affects and is affected by all the others. Eventually, running the simulation, elements will show a coherent behaviour according to the model's composed interactions. The primary aim was to experience how this behaviour affects sound and its spatial appearance. Depending on the relations governing the internal mechanics, these systems exhibit dynamics that lie within a continuum ranging from single organic "entities", to extended subspaces, or to a collection of disjoint particles. Exploring this range of possibilities and making it subject to composition, was a central aim of this exploration.

This approach is applied in parallel to different time scales of sound generation and spatialisation, three distinct systems or layers where used to compose the choreography of sound in space. We refer to these as *micro-scopic*, *meso-scopic* and *macro-scopic* respectively. Each work on different time steps and rates, ranging from sampling rate (*micro*) in terms of sound synthesis to much slower transformations and bigger time steps when it comes to sound spatial distribution (*macro*).

- The *microscopic* layer is realised with a simulation that therefore acts on the smallest times steps, i.e. audio-rate. Displacements of the particles are directly audified: this modelling layer is therefore the sound generator, responsible for its morphology at small time steps, its microstructure.

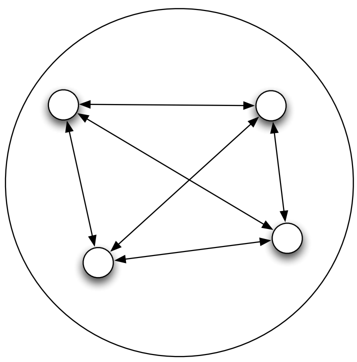


Figure A.6: Graphical depiction of the *microscopic* layer: the four empty dots represent masses interacting with each other and bound in a spherical region (the solid line boundary)

The model for this layer (see figure A.6) is constructed from a network of four mutually interacting masses, whose movements are confined within a sphere with an elastic boundary. The values of the speeds of these interacting masses at every audio-rate time step are translated into sample values in a four-channel audio stream. The weights of these particles' masses and the magnitude of the forces connecting them to each other have been chosen such that their movements exhibited changes with frequencies within the audible range. The morphology of the sound output is thus a function of the weight, of the forces connecting the masses to each other and of the attrition acting on them. For instance, spring-like forces lead to simple, relatively static harmonic spectra. Gravitational like forces instead produce more complex and inharmonic sounds with unstable and changing time behaviour. With attractive forces, the sound exhibits clear pitches while repulsive forces on the contrary cause more impulsive, noisy sounds or bursts. During the preceding preparation phase, the different spatial perceptions were examined independently as a function of the different sound microstructures in dependence of the parameters of the model. Varying those, a "behavioural" space can be identified, encompassing a range of distinguishable timbres, ranging from harmonic to quasi-harmonic to transient. While the installation was in operation, these parameters were gradually changed therefore exploring this space of possible behavioural states. Two of these models, oscillating between different states run in parallel in the installation, yielding substantial timbral variation, juxtaposing different sonic textures and thus enhancing a differential perception of their specificity.

- The *meso-scopic* modelling layer (and the *macroscopic*, see below) are tightly connected to how the sound produced by the *microscopic* layer is projected through the loudspeaker array.

  This layer (figure A.7 top), was implemented using five particles interacting through gravitational-like forces. The model was designed so that one of the objects acted as main attractor, keeping the other four orbiting around it: its mass was substantially larger than the masses of the other four particles and the forces connecting the lighter objects to the attractor were substantially stronger than the ones connecting them to each other. Masses and forces were chosen such that the movements were significantly slower than in the

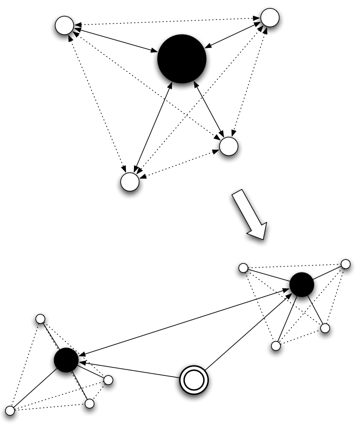


Figure A.7: Top: *meso-scopic* model. Five masse interact with each other through gravitational forces. The black object is bigger and heavier then the other four. Bottom: *macro-scopic* model. The central fixed object acts on the black masses of the previous model attracting them; at the same time these objects repulse each other previous *microscopic* model: the time needed for one of the smaller objects for a complete revolution was ca. $1-3$ seconds. This model was also updated dynamically, changing the magnitude of the attractive forces and yielding variable spatial configurations with objects moving in a loose or tighter way relative to each other, ending up very concentrated or more dispersed. The location of each object in this *mesoscopic* model defines where the sound (i.e. the displacement) each mass in the microscopic model produces, would appear on the loudspeaker array: that is, the movement of the single particle in the *microscopic* model are spatialised, not their sum or a mix. The qualities of their movement and their relative positions relate to how localized or extended the sounds projected by the loudspeaker array would be perceived.

- The *macro-scopic* modelling layer connects to the movement (and rotation) of the *meso-scopic* model layer in itself and in relation to the whole space defined by the loudspeaker array.

  A similar approach was used here as in the previous layer. Again, a bigger mass, a fixed "sun", was placed at the origin of the coordinate system. The two bigger attractors of the *meso-scopic* level revolve around this object as they are attracted by it with gravitational forces. These are also mutually repulsing each other through similar gravitational forces so that the *meso-scopic* systems slowly revolve around this central sun, still remaining mostly well separated from each other and only occasionally mixing (Figure A.7 bottom).

In effect, there are two disjoint models working in parallel: the *microscopic* on the one hand and the *macro-scopic* and *meso-scopic* on the other. The latter systems share the same simulation space, a rectangular box with reflecting walls which constrains the movement of their elements.

As has been already mentioned, this installation uses a loudspeaker array, the *The IEM modular speaker array system*. A 48 channel system that uses affordable Class-D amplifiers and small, easy-to-mount speakers, which provides the opportunity to rapidly prototype and quickly test diverse speaker array configurations. For *interstices* the 48 speaker array has been divided in four speaker clusters each containing twelve speakers (see A.9 and A.10).

For the spatialisation, an approach loosely leaning towards the Virtual Microphone Control (ViMiC) approach[7] mixed with a modified DBAP algorithm (see DBAP and ADBAP) has been used. Therefore, the simulation space is put in tight correspondence with the physical exhibition space by

[7] Jonas Braasch. A loudspeaker-based 3d sound projection using virtual microphone control (vimic). In *Audio Engineering Society Convention 118*. Audio Engineering Society, 2005; and Nils Peters, Tristan Matthews, Jonas Braasch, and Stephan McAdams. Spatial sound rendering in max/msp with vimic. In *Proceedings of the 2008 International Computer Music Conference*, 2008

establishing a simple correspondence which maps specific positions in this space with the actual loudspeakers positions in the array. Each speaker was represented in the *macro* and *meso-scopic* system space using a single point. The sound of each of the *micro-scopic* model masses was rendered to the loudspeakers with an intensity that was determined based on the distance of its corresponding *meso-scopic* mass to each of those loudspeaker points. To avoid an excessive *blurring* of the single sources, the algorithm is parametrized so that each sound could appear on a maximum of three loudspeaker at the same time (see figure A.8).

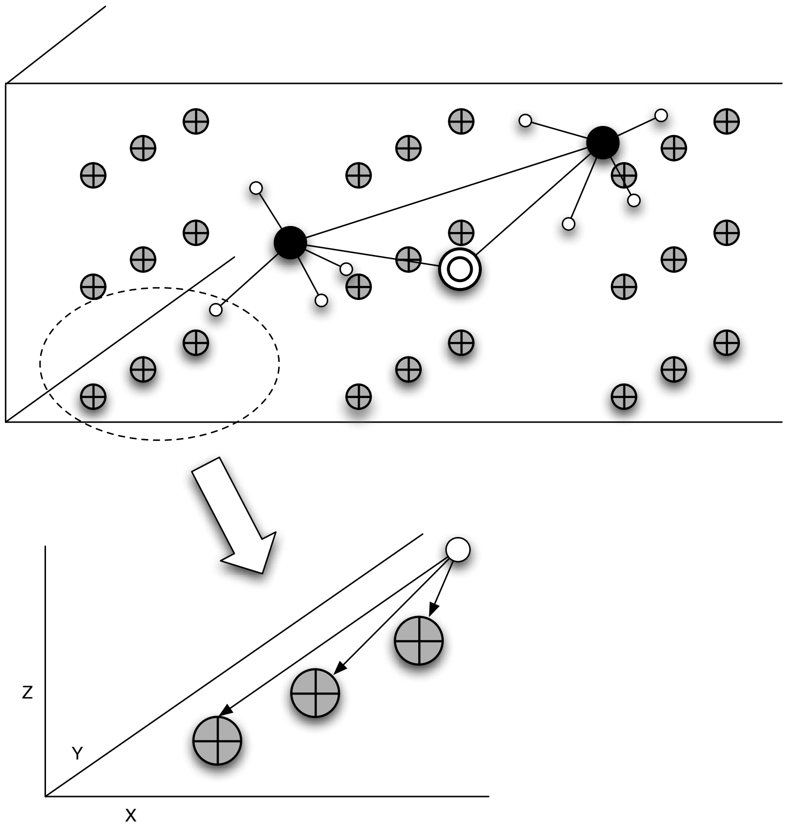


Figure A.8: Graphical representation of the spatialisation algorithm used in *interstices*

A.5 Zwischenräume

Some of the paragraphs the following section are based on parts of the paper "Zwischenräume - a case study in the evaluation of interactive sound installations" by Georgios Marentakis and David Pirrò, which appeared in the Proceedings of the International Computer Music Conference 2014

Zwischenräume is an interactive sound installation which can be understood as an evolution of the *interstices*

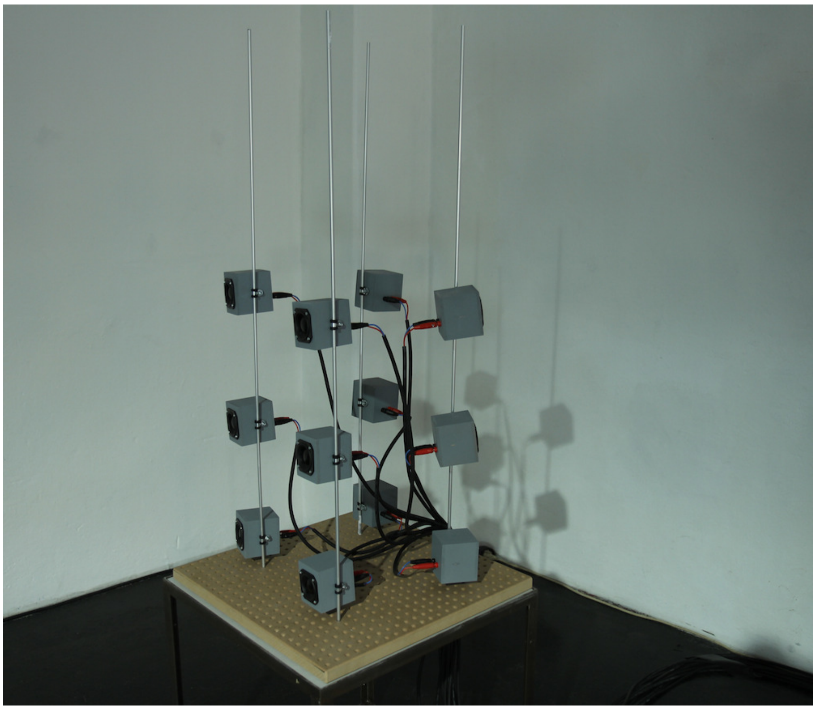


Figure A.9: One of the loudspeaker clusters used in the sound installation *interstices*. Foto: Martin Rumori

Figure A.10: Final distribution of the loudspeaker clusters in the ESC Labor space. Foto: Martin Rumori

installation (Interstices) and a continuation of the collaboration with Georgios Marantakis. The installation, however, takes a more clear-cut and "radical" approach addressing more directly in an artistic setting some aspects at the core of a dynamical systems inspired composition of interactive sound environments.

This work was developed as part of the *Klangraüme* (2013–2015) project I was part of together with Georgios Marentakis (Project Leader) and colleague Marian Weger. The research project looked into how evaluation strategies common in *HCI* and the field of *Sonic Interaction Design* research could be applied to interactive artistic sound installations and which consequences and effects the application of those methods have both on artistic praxis and on evaluation methods themselves.[8] In the context of this research project, the installation was thus also the object of an evaluation.[9]

The idea behind the installation *zwischenräume* was that of an interactive environment which would be experienced as an organic entity continuously sensing the space, reacting to sonic events, and providing dynamic sonic spatial perspectives depending on the visitors' actions or their mere presence. Interaction with the installation is made possible only through sound which functions both as the input and output channel for the system.

Di Scipio's approach to interactive systems as ecosystemic systems[10] was central to the conception and development of the installation. In this sense, visitors and installation are regarded as equal agents that share the same space. Through their mutual interaction, an evolving dynamical system emerges. Interactivity is conceived as a continuous exchange between these actors; an exchange that affects the state of both of them through an adaptation process that eventually *resonates* in a state, a particular and recognisable *behaviour*. In the context of this work, my working definition of *behaviour* was according to following Arturo Rosenblueth's and Norbert Wiener's formulation:[11]

> *By behaviour is meant any change of an entity with respect to its surroundings. This change may be largely an output of the object, the input being then minimal, irrelevant or remote; or else the change may be immediately traceable to a certain input. Accordingly, any modification of an object, detectable externally, may be denoted as behaviour.*

This "definition" is of course too extensive for being useful, as also the author suggests. Still, it forms a good basis for further characterisation. Especially, in the context of this installation, the main focus lied in the composition of behaviour as change which unfolds both in the time domain and in the *spatial* domain and of the *detectable* quality of this change: that is, the behaviour the installation would expose, would be a clearly detectable, or better, sensed as such by the visitors as a trace of their actions in the space. In the words of Rosenblueth, a *purposeful* behaviour as directed to the attainment of particular condition and opposed to *purposeless* i.e. random behaviour.

On this basis, three specific scenarios or separable *eigenbehaviours*[12] were developed. These eigenbehaviours were then recomposed using a dynamical system that

[8] Unfortunately there is no space here for diving into questions and outcomes of this project. More information however can be found here: http://iem.kug.ac.at/klangraeume/klangraeume.html, accessed on the 17/07/20170

[9] Georgios Marentakis, David Pirrò, and Raphael Kapeller. Zwischenräume - a case study in the evaluation of interactive sound installations. In *Proceedings of the Joint 11th Sound and Music Computing Conference and the 40th International Computer Music Conference*, pages 277-284, Athens, 2014

[10] Agostino Di Scipio. 'Sound is the interface': from interactive to ecosystemic signal processing. *Organised Sound*, 8(3):269-277, 2003

[11] Arturo Rosenblueth, Norbert Wiener, and Julian Bigelow. Bahvior, purpose and teleology. *Philosophy of Science*, 10(1):18 - 24, January 1943

[12] Heinz Von Foerster. Objects: tokens for (eigen-)behaviors. *Understanding understanding: Essays on cybernetics and cognition*, pages 261-271, 2003

orchestrated their temporal and spatial evolution depending on the state of environment and installation or on how the visitor would interact.

The aforementioned concepts were framed by conceiving the installation as a feedback system: sound picked up by microphones is projected back into the room with a specific delay. Feedback systems exhibit dynamically evolving behaviour which served as the basis for the eigenbehaviours developed. In particular, by varying the time delay a rich palette of distinct sonic experiences emerges ranging from feedback tones, to the perception of spaciousness and possibly to echo effects.

The development revolved around the spatial, temporal and energy relationships between the location of microphones picking up sound and the loudspeakers projecting it back. Necessary tools were a simple location detection algorithm, implemented by determining which microphone received the maximum input at any time, and a ring buffer system that allows an efficient control of the delay and the gain of the output of each loudspeaker. All these tools were developed in *rattle*.

The installation was realized using the 48 loudspeakers system already mentioned in Interstices and complemented with an array of 24 microphones. The first staging decisions related to the placement of the loudspeakers and the microphones. With respect to the loudspeakers, a positioning that would structure the space less rigidly was sought, in order to allow the visitor more freedom in choosing which paths to take through the space and installation. Loudspeakers were thus distributed quasi-randomly (see figure A.11), forming small clusters in the exhibition space. Various kinds of objects were used to mount the loudspeakers (music stands, microphone stands, tables, wooden blocks) to underline the playful character of the installation. As a consequence this configuration provoked spatial heterogeneity and local behaviour as the different loudspeakers clusters projected sound slightly differently. Finally, to emphasise the fact that the installation reacts to the sonic activity in the room, some sound producing objects (a snare drum, some squeaky ducks and a trampoline with some bells attached under it) were distributed in the space.

In contrast to the loudspeakers, the microphones were hung from the ceiling in a very regular fashion. The exhibition area was covered with a regular lattice, in which microphones were placed with a fixed distance between them (see figure A.11). The desktop computer running the installation, the audio interfaces and AD/DA converters, amplifiers and pre-amplifiers were stacked vertically

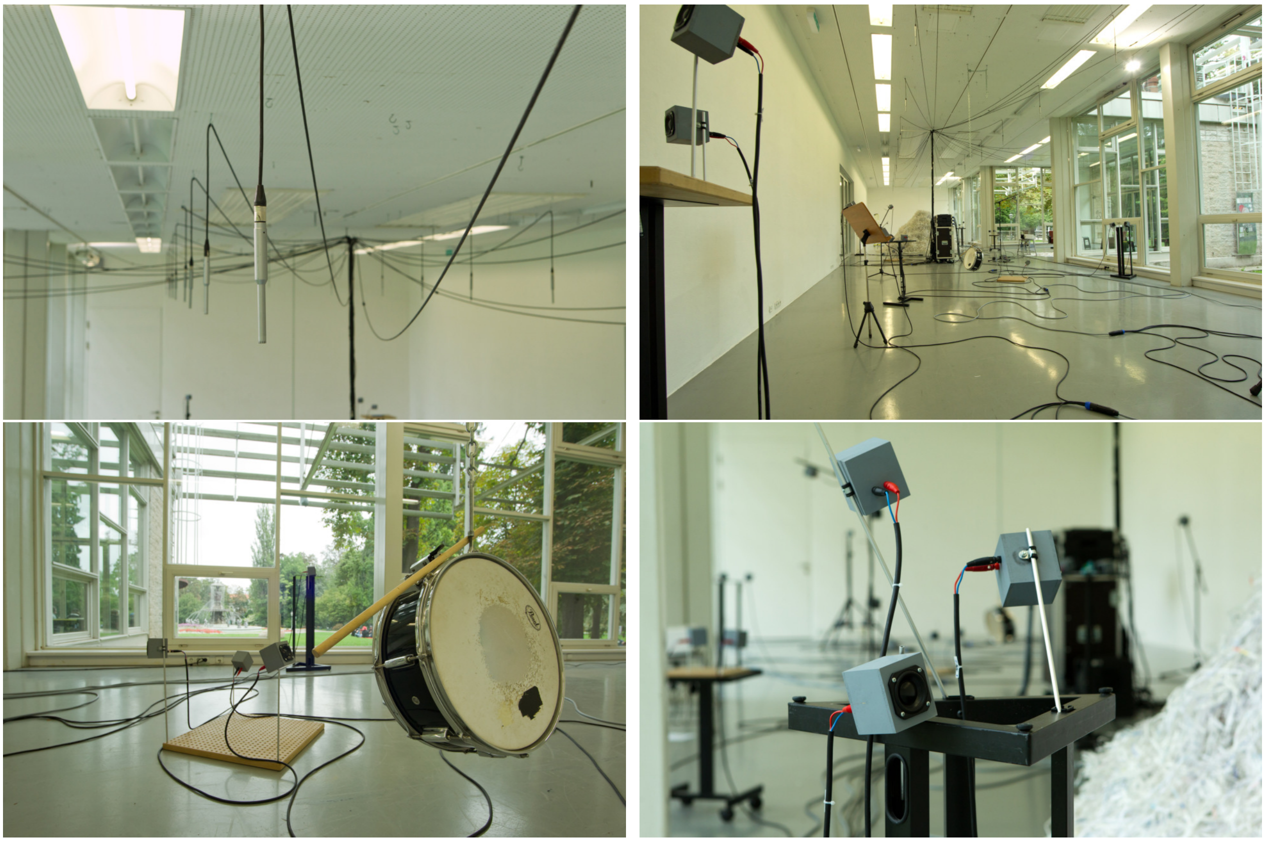


Figure A.11: Photos from the final installation setup in the Forum Stadtpark exhibition space.

within a box standing roughly at the centre of the room. Therefore, all signal cables formed a star shaped stem as they connected to the sound system. Although hiding the cabling was appealing to us, for practical as well as aesthetic reasons, we decided to use it as a visual element of the installation and to shape it consciously.

The scenarios for *interstice* have been developed in a preliminary experimentation period aiming at developing a repertoire of clearly separable scenarios or eigenbehaviours yielding interesting and perceptually distinct sonic outcomes. These scenarios were fixed as parametrisations of the system exposing a special behaviour with respect to its interactions with the visitor and the environment. Finally, a physical model was conceived that would re-compose these scenarios into a single installation. The model would expose either one or oscillate between two or more scenarios according to the visitors' activity in the room. The three scenarios and the physical model that were eventually chosen for the installation are presented in the next paragraphs.

- The *feedback* scenario directly exploits the feedback phenomenon (i.e. the so-called *Larsen* tones) that occurs when no or very little delay exists between input and output. In the most simple case, feedback manifests as tones, whose frequency depends on the main resonant frequencies of the room and its acoustic characteristics. However, when many loudspeakers with quasi-random orientations and locations are used as output and many microphones as input, more resonant frequencies can be excited simultaneously producing complex spectra. To allow for spectral variability however the main resonant frequencies need to be suppressed as they would otherwise dominate and lead the system into similar states. This can be achieved using a limiter and a peaking filter bank to control the overall amplitude of the feedback tones and the time needed for these tones to appear. Adapting the filter bank allows direct control over the "inertia" of the system, that is the system sensitivity to changes in the environment and the ease with which a transition between different feedback states occurs. Calibrating gain factors, filters and limiters was challenging as the feedback system strongly depends on the particular space and the loudspeaker and microphone spatial positioning. It was however possible to find configurations in which complex feedback tones were produced whose spectra depended on the listening location and the mere visitors' presence. In particular, the nearer the visitor was to a loudspeaker (or even holding a hand directly in front of a membrane), the more dramatic and fast were the reactions of the system. It has to be noted that this is the only scenario in which the installation was producing sound apparently on its own.

- In the *Hall and Echo* scenario the delay between input and output was increased creating a spatially distributed reverb effect, increasing the perceived acoustic size of the room. With even longer delays, echoes would appear that would propagate onto the loudspeaker leading to an impression of spatial spreading of the sound. Moreover, the feedback of the echoes into the system through the microphones, yielded further softer echoes that eventually smeared uniformly over the whole array and slowly disappeared. By adjusting the spatial distribution of the loudspeakers, the effect of echoes from specific loudspeakers on specific microphones can be changed leading to the appearance of prominent spatial heterogeneity. It could happen that echoes would "hang" between some loudspeakers and microphones never disappearing or even continuously growing louder. To avoid this we introduced a calibration step by which loudspeaker gains were recomputed so that the maximum *RMS* value from each loudspeaker measured on the microphone array was equalised. This operation allowed more control and more stability in the overall system. Refining this scenario, gain and delay times were chosen such that the delayed signal was just on the threshold of being perceived as an echo. Therefore a reverb effect would emerge for continuous sounds (e.g. whistling), due to the temporal overlap of the sound with the echo onsets. In contrast, for impulsive sounds, the perception of echoes would be accentuated given the temporal distinction between sound offset and echo onset.

- The *Paths* scenario is derived from the previous and restructures it in order to provide the impression of auditory movement; echoes that slowly "crawl" in space, departing from the location the sound was produced and moving along clearly perceivable, dynamic and changing paths through the loudspeaker array. To reinforce echo perception, delays here operate past the echo threshold. Sound captured by the microphone closest to the sound producing action is recorded and played back delayed from the nearest speakers. Using an adjustable delay the same sound is projected to the one or two loudspeakers closest to the previous with a slightly attenuated amplitude. As this process is repeated, a path of echoes is created, propagating from one loudspeaker to the other and eventually, after a period that depends on an attenuation factor, disappears. We intentionally avoided propagation paths in fixed directions in space (e.g. all paths moving towards one side of the room) and paths that would recirculate between a small number of loudspeakers. In order to minimise the effect recapturing subsequent repetitions that would obscure the development of the paths in space, the signal from the one microphone receiving maximum energy was used as source while the input gain for all other microphones was strongly diminished. Only sound exceeding a specific threshold would be used as sources for this scenario. Particular to this scenario is that it explicitly advocates interaction between the visitor and the installation. In contrast to the previous scenarios, the effect of the acoustic environment is limited, making the behaviour of the installation's response completely dependent on the actions and sonic events produced by the audience.

- The goal of the *physical model* is to operate on the parameter space defined by the previous scenarios and synthesise their behaviour. In the model, both loudspeakers and microphones were defined as elements (masses) placed in locations that resembled their actual positions in the exhibition space, with microphones above the loudspeakers plane. All these objects were connected by forces. The masses representing the microphones exerted gravitational forces on the neighbouring loudspeakers masses. These, in turn, exerted and were affected by fixed spring-like forces exerted by their nearest neighbours. When a microphone received a signal above a certain threshold, it "pulled" the loudspeakers it was connected with, with a force proportional to the signal's energy, thus exciting the whole system mesh of loudspeakers. This threshold was high enough to allow the whole system to relax when sound in the room was soft. The result was a mesh that, when excited, would behave much like a plate. An excitation would be transmitted to all loudspeaker masses in the model and the whole mesh would slowly wobble back to a resting state within a time frame determined by the inertia of the masses and the attrition we used. Using *rattle*, the simulation of this model was run in real-time at audio rate.

The displacement of the loudspeakers along the z axis (towards the microphones) was used to control the delay with which captured sound would be reproduced by the connected loudspeakers: ranging from zero when at rest position to values appropriate for the hall and echo scenario. Velocity along the z axis was used to control the gain of the loudspeakers: ranging from a lower threshold suitable to the feedback scenario (mass at rest) to a value appropriate for the echo scenario. Speed along the direction connecting one loudspeaker mass to its neighbours (paths scenario) was used to control the amplitude with which the signal was reproduced by the next mass. The displacement of the loudspeaker masses was mapped to the delay factor with which the repetitions were reproduced along the paths.

The effect of these choices was that when the masses were at rest i.e. when there was little or no activity in the room, the installation would fall into the feedback scenario. As soon as a sound or a feedback tone appeared, the microphone masses would start to pull the loudspeakers. Feedback tones would slowly disappear as the excitation would spread over the whole mesh and the hall and echos scenario would appear. Louder sounds and much activity in the room, would result in greater displacements and speeds of the loudspeaker masses and the path scenario would eventually appear. Connecting the real-time physical model's state with the parameters of the scenarios, allowed us to recompose and merge the three single eigenbehaviours into one. Fine tuning these mappings was a process that took a long time, but eventually converged into the realisation of one system that would be perceived as coherent, exhibiting a global behaviour that exposed the three scenarios in dependence of the overall activity in the space.

In the evaluation phase, visitors were observed during their stay in the installation space and interviewed afterwards: interviews were then transcribed and analysed using the method of constant comparisons and a combination of open and selective coding within the grounded theory framework.[13] All participants perceived not only that the installation was reactive with respect to their presence or actions, but also that "it" exhibited a sort of identifiable behaviour. Quite often statements classified under the behaviour category overlapped with statements under the interaction category. This is not surprising as the installation behaviour was meant to manifest itself through interaction with the visitors.

Visitors interacted with the installation in a primarily playful and explorative way. The installation was thus interpreted as a rich medium where different perceptions could be created and observed, a pattern that was also quite evident in the video recordings.

[13] Barney Glaser. *Discovery of grounded theory: Strategies for qualitative research*. Routledge, 2017; and Juliet Corbin and Anselm Strauss. Grounded theory research: Procedures, canons and evaluative criteria. *Zeitschrift für Soziologie*, 19(6):418-427, 1990

B

rattle *integration algorithms*

When it comes to simulation, the heart of every algorithm lies in the choices made regarding how **numerical integration** is performed. That is, how the problem of calculating the definite integral of a general function f between two limits $a < b$

$$\int_a^b f(x)dx \tag{B.1}$$

is solved. This problem is central in computational physics, the research field dedicated to develop and analyse numerical operations in order to solve systems of differential equations. In this context the above operation is called is called **quadrature** in order to distinguish this operation from the integration process of analytically solving (i.e. finding the mathematical equations) the above equation[1].

[1] Steven E Koonin, Dawn C Meredith, and William H Press. Computational physics: Fortran version. *Physics Today*, 44:112, 1991

Many different methods have been devised to tackle the problem, having different strength and weaknesses: the most important aspect of these numerical operations is that all these methods are *approximations* and thus affected by error. The understanding of how this error affects the found numerical solution, identifies two distinguishing characteristics of each method, its *order*, its *stability* and the *computational effort* it needs:

- the *order* of a method indicates how big the error of the method is with respect to the segment length $b - a$: higher order means the method produces smaller errors
- the *stability* of the method refers to the property of the algorithm of magnifying (instability) or not (stability) the above error when it is repeatedly applied
- the *computational effort* refers to the number of operations needed by the algorithm to calculate the result. Specially in a framework like rattle, where quadrature operations are performed in real-time at audio rate, this aspect plays an important role. In general, less *computational effort* means smaller *order* and therefore worse approximations,

so finding a good balance between these two aspects is central.

In general in the present work we are dealing with *initial value problems* for ordinary differential equations: we are looking for $x(t)$ functions which are solutions to

$$\dot{x}(t) = f(x(t)) \tag{B.2}$$

given the value

$$x(t_0 = 0) = x_0 \tag{B.3}$$

for some initial time t_0: it is easy to see that this kind of problem reduces to a similar operation as in eq B.1 as we need to integrate $f(x)$ in order to find $x(t)$. This kind of problem occurs for example if we are given the momentum of a particle and its position as time t_0 and wish to know it position at some later time. If the function $f(x(t))$ is a continuous function $x(t)$ is also continuous and can therefore be expressed in terms of its derivatives $\dot{x}, \ddot{x}, \ldots$ using a *Taylor series* to expand it in the neighbourhood of $t = 0$:

$$x(t) = x_0 + \dot{x}\,t + \ddot{x}\frac{t^2}{2!} + \dddot{x}\frac{t^3}{3!} + \ldots \tag{B.4}$$

where the derivatives are evaluated at $t = 0$.

Specifically, in our case, we are interested in the value of $x(t)$ at particular values of t that are integer multiples of some fixed step h:

$$x_n = x(t = nh) \quad f_n = f(x_n) \quad n = 0, \pm 1. \pm 2, \ldots \tag{B.5}$$

e.g. h could be, as in the case of *rattle*, the time interval between two audio samples, $1/44100 = 2.26e^{-5}$ seconds for a $44100Hz$ sampling rate. The above expansion in eq B.4 becomes at $nt = \pm 1$

$$x_{\pm 1} = x_0 \pm \dot{x}_0 h + \ddot{x}_0 \frac{h^2}{2} + O(h^3) \tag{B.6}$$

where $O(h^3)$ stands for the terms of order h^3 or higher. Assuming that x and its derivatives are all approximately of the same order of magnitude, as it is the case in many physical system, these higher order terms will get smaller and smaller for higher powers if h is chosen small enough.

From the previous equation focusing only on the lower order terms we can easily derive the *forward and backward difference formulas*:

$$\dot{x}_0 \approx \frac{x_1 - x_0}{h} + O(h) \tag{B.7}$$

$$\dot{x}_0 \approx \frac{x_0 - x_{-1}}{h} + O(h) \tag{B.8}$$

Equation B.7 thus readily leads to *Euler's method* or also *forward Euler method*, the simplest of all quadrature algorithms, which for any n and $n+1$ and using eq B.2 becomes

$$\frac{x_{n+1} - x_n}{h} + O(h) = f_n \tag{B.9}$$

and therefore

$$x_{n+1} = x_n + f_n h + O(h^2) \tag{B.10}$$

which gives us a method for calculating the next step of the trajectory $x(t)$ given x_n. On the one hand, this method has a very low *computational effort* and thus is very attractive for time critical applications as audio synthesis applications, but on the other it is neither very accurate (the step's error is just of second *order* i.e. $O(h^2)$) nor it is very *stable*.

The *numerical stability* of a method is established by applying the method to the numerical solution of a simple differential equation[2]:

$$\dot{x} = \lambda x \tag{B.11}$$

which has the analytical solution

$$x = e^{\lambda t} x_0 \tag{B.12}$$

with λ a complex number. $x_0 = 1$ usually. If $Re\{\lambda\} < 0$ the solution is analytically stable as all possible trajectories remain bounded as time tends to infinity (see figure B.1).

[2] Abbas I Abdel Karim. Criterion for the stability of numerical integration methods for the solution of systems of differential equations. *J. Res. NBS*, 718, 1967

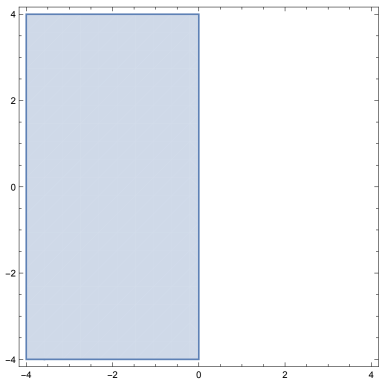


Figure B.1: In blue the region in the complex plane of analytical stability of the solution of equation B.11

Applying the forward Euler method to the numerical solution of equation B.11 thus using equation B.10 we get the following iterative rule:

$$\begin{aligned} x_1 &= x_0 + \lambda h x_0 = (1+\lambda h)x_0 \\ x_2 &= x_1 + \lambda h x_1 = (1+\lambda h)x_1 = (1+\lambda h)^2 x_0 \\ x_3 &= (1+\lambda h)^3 x_0 \\ &\vdots \\ x_n &= (1+\lambda h)^n x_0 \end{aligned} \tag{B.13}$$

Equation B.13 describes a stable system for $n \to \infty$ if

$$|1+\lambda h| < 1 \tag{B.14}$$

which is a disc of radius 1 in the complex plane of λh as depicted in figure B.2. As we can seen the region of numerical stability of the method is very small and does not cover the whole region of stability the analytical solution has. That is, the forward Euler method does a poor job in approximating the analytical solution.

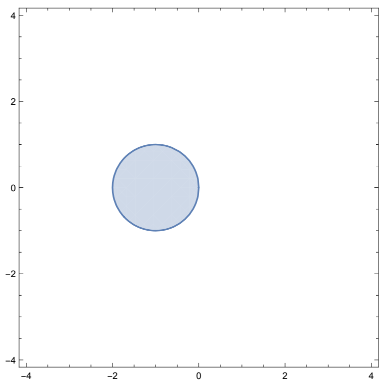


Figure B.2: Region of numerical stability of the forward Euler method in the complex plane λh.

This can be easily seen with an example. We can for example consider the equation B.11 with $k = -2.3$ and $x_0 = 1$,

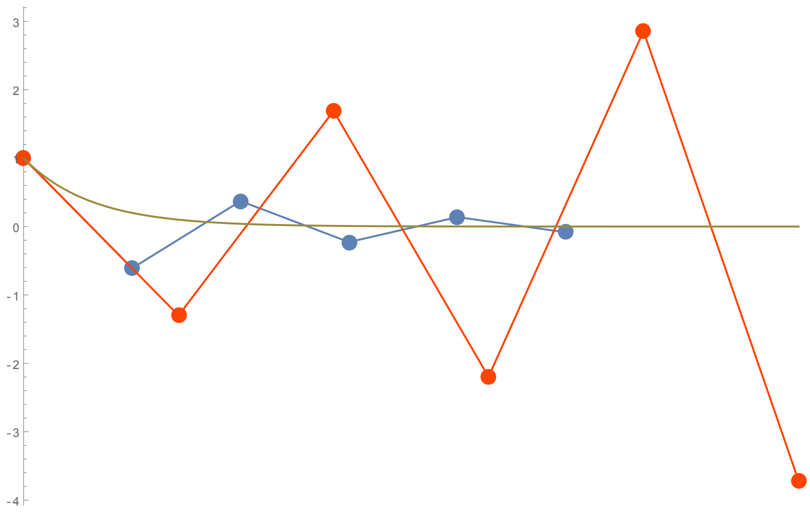


Figure B.3: Plot of the solution to the differential equation $\dot{x} = -2.3x$: in green the exact solution $x = e^{-2.3t}$, in blue the solution computed with the forward euler method and $h = 0.7$, in orange the solution computed with the forward euler method and $h = 1$ which is unstable

which gives the stable analytical solution $x = e^{-2.3t}$. Applying the forward Euler method to this problem and choosing $h = 0.7$ we would be in the stability region as equation B.13 indicates. As depicted in figure B.3 after a short initial oscillating region, the method would be stable. Choosing instead $h = 1$ would mean being outside the stability region and therefore unstable. We could see that the method would produce oscillating solutions growing in amplitude. The method is thus extremely sensitive to the right choice of the step h which should be small enough. This instability is particularly evident for oscillatory solutions of the B.11 equations, i.e. when $Im\{k\} \neq 0$, which are of particular interest to us: in this case, even with a very small step size with respect to the frequency of the system, the method would always be unstable, the energy of the system growing exponentially.

Taking equation B.8 instead would lead to to a different iterative method, known as *backward* or *implict Euler*:

$$\frac{x_{n+1} - x_n}{h} + O(h) = f_{n+1} \tag{B.15}$$

and therefore

$$x_{n+1} = x_n + f_{n+1}h + O(h^2) \tag{B.16}$$

Even if this method seems very similar to the previous, it is exhibits substantial differences. The *numerical stability* analysis of this method, applying the previous process, would lead to:

$$\begin{aligned} x_1 &= x_0 + \lambda h x_1 \Rightarrow x_1 = \frac{1}{(1+\lambda h)} x_0 \\ x_2 &= x_1 + \lambda h x_2 \Rightarrow x_2 = \frac{1}{(1+\lambda h)} x_1 = \frac{1}{(1+\lambda h)^2} x_0 \\ &\vdots \\ x_n &= \frac{1}{(1+\lambda h)^n} x_0 \end{aligned} \tag{B.17}$$

which would be stable if

$$\frac{1}{|1+\lambda h|} < 1 \tag{B.18}$$

As shown in figure B.4, the shape of stability region of this method is very different than in the former method. As can be seen, on the one hand the method does a very good job in approximating solutions for the stable region of the analytical solution. On the other side, it produces stable solution even where the analytical solution gives unstable i.e. growing, solutions, in the complex half plane $Re\{\lambda\} > 0$

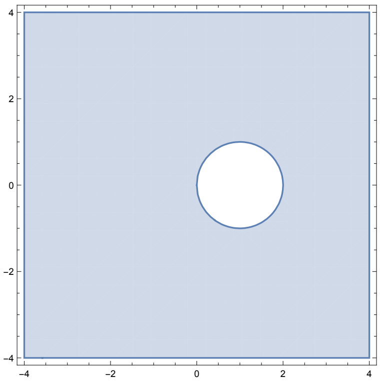


Figure B.4: Region of numerical stability of the backward Euler method in the complex plane λh.

Furthermore, the method, as all other *implicit methods*, presents an ulterior difficulty. In fact, reformulating equation B.16 taking into account that $f_n = f(x_n)$, we see

$$x_{n+1} = x_n + f(x_{n+1}) \tag{B.19}$$

that the term x_{n+1}, which we want to find, is on both sides of the equation: this is the fundamental characteristic of all implicit methods. As a consequence one needs to solve an *algebraic equation* in the unknown x_{n+1}: this problem can be reformulated as to find the roots of the function $g(x_{n+1})$:

$$g(x_{n+1}) = x_{n+1} - x_n - f(x_{n+1}) = 0 \tag{B.20}$$

that is the points x_{n+1} for which this function is zero. This can in general be a very difficult problem to solve numerically as f could be any non-linear function. Usually this kind of problems are solved with iterative methods such as the *Newton-Raphson method* which drastically increase the computational effort.

Both above methods are therefore not well suited to be implemented in a software framework which needs to perform fast and stable (i.e. at audio rate) numerical integration.

Of course the forward and backward Euler are the most simple numerical methods, but they show on which mathematical concepts those methods are constructed and tested. Usually methods which produce better results are constructed using two principal paths.

Linear multisteps methods (also known as the *Adam-Bashford methods*) depart from a slightly different formulation as in equation B.4 to compute $x(t)$. From equation B.2

$$x(t_1) = x(t_0) + \int_{t_0}^{t_1} f(x(t))dt \tag{B.21}$$

that is in discrete time steps:

$$x_{n+1} = x_n + \int_{n}^{n+1} f(t)dt \tag{B.22}$$

the derivation of these methods follows the idea to approximate better the value of the integral of the function f by taking into account its value at previous time steps and thus producing linear, quadratic, cubic, etc. polynomial approximations of f. This leads to a whole family of higher order explicit or implicit methods. As an example the explicit methods following the linear and cubic approximation of f would be respectively:

$$
\begin{aligned}
x_{n+1} &= x_n + h\left(\frac{3}{2}f_n - \frac{1}{2}f_{n-1}\right) \\
x_{n+1} &= x_n + h\left(\frac{23}{12}f_n - \frac{4}{3}f_{n-1} + \frac{5}{12}f_{n-2}\right)
\end{aligned}
\tag{B.23}
$$

and the respective implicit methods would be:

$$
\begin{aligned}
x_{n+1} &= x_n + h\frac{1}{2}\left(f_n + f_{n-1}\right) \\
x_{n+1} &= x_n + h\left(\frac{5}{12}f_n + \frac{2}{3}f_{n-1} - \frac{1}{12}f_{n-2}\right)
\end{aligned}
\tag{B.24}
$$

The *Runge-Kutta method* family comprises very widely used numerical integration algorithms which instead use higher order expansions of the the Taylor series in equation B.4 to better approximate the integral of the function f. The so derived second order method algorithm would be:

$$
\begin{aligned}
k &= hf(x_n) \\
x_{n+1} &= x_n + hf(x_n + \frac{1}{2}k)
\end{aligned}
\tag{B.25}
$$

and the widely used fourth order method:

$$
\begin{aligned}
k_1 &= hf(x_n) \\
k_2 &= hf(x_n + \frac{1}{2}k_1) \\
k_3 &= hf(x_n + \frac{1}{2}k_2) \\
k_4 &= hf(x_n + k_3) \\
x_{n+1} &= x_n + \frac{1}{6}\left(k_1 + 2k_2 + 2k_3 + k_4\right)
\end{aligned}
\tag{B.26}
$$

These methods can be very accurate and exhibit better stability properties, but involve the computation of the the value of the function f multiple times for each time step.

In *rattle* a different kind of integration scheme is used, a *symplectic scheme*. This particular method can be used in the numerical integration of a special class of problems of the form of the B.1 equation called *Hamiltonian* *systems*, systems of *coupled* differential equations and ground on Newton's second law:

$$m\dot{v} = F(x) = -\frac{dU(x)}{dx} \quad \text{(B.27)}$$

$$\dot{x} = \frac{dv}{dt} \quad \text{(B.28)}$$

which describes how a mass under the influence of the force F, or a potential field U accelerates. To understand these methods, a small step backwards into theory is necessary.

Hamiltonian systems[3] are dynamical systems which can be described with the Hamiltonian function which embodies Newton's second law of mechanics and are of utmost interest in physics: they are used to describe most systems found in nature from planetary system to the motion of an electron in an electromagnetic field. These equations depend on the characteristics of the Hamiltonian function H which depends on position, velocity of the involved elements (masses) and time. The special interest in physics for this function derives from the fact that the Hamiltonian[4] is for these systems the sum of the kinetic and potential energies T and U:

[3] Herbert Goldstein, Charles Poole, and John Safko. *Classical mechanics*. Addison Wesley, 2002

[4] For the sake clarity and conciseness, I'm following a simplified mathematical treatment of this section trying to bring across the most important concepts qualitatively. Further I will use, as in most texts, the *generalised coordinates* notation for position and momenta, q and p respectively. Therefore in the next equation, I assume separable Hamiltonians (the potential U is not dependent of the momentum q).

$$H(q,p,t) = T(p) + U(q) \quad \text{(B.29)}$$

For instance the Hamiltonian of the simple harmonic oscillator would be:

$$H = \frac{p^2}{2m} + \frac{1}{2}kx^2 \quad \text{(B.30)}$$

Thus, usually the Hamiltonian is the energy of the formulated system and for *closed systems*, given the conservation of energy, it is constant and time independent:

$$\frac{\partial H}{\partial t} = 0 \quad \text{(B.31)}$$

A principal characteristic of this function is that it describes the *evolution* of the state of the dynamical system, i.e. it describes how the coordinates q and p evolve in time via the so called *Hamilton equations*, a system of differential equations of the general form of equation B.2:

$$\dot{p} = -\frac{\partial H}{\partial q} \quad \text{(B.32)}$$

$$\dot{q} = \frac{\partial H}{\partial p}$$

Considering the space spanned by the coordinates (q,p), the *phase-space*, the integration of the former equations results in a so-called *flow* in this space. To any (continuous and differentiable) Hamiltonian corresponds thus a *flow* ϕ_t which describes the time evolution of the system which, given any initial coordinate in the phase-space (q_0, p_0), returns the point (q, p) to which the system would evolve at any time t:

$$\phi_t : (q_0, p_0) \to (q(t), p(t)) \tag{B.33}$$

An important characteristic of this function is that, for Hamiltonian systems, it is a so-called *symplectic map*[5] that means that this function preserves area in the phase space. In other words, given a section of the phase space, transforming this section with a symplectic map would "transport" it to different section in the phase-space, which could be different in form, but would have the same area (see figure B.5).

[5] This descends from a 1899 Theorem by Poincarè, published in *Les Methodes Nouvelles de la Mecanique Celeste*.

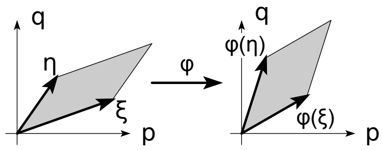


Figure B.5: Simplecticity (area preservation) of the mapping ϕ_t

This quality of the Hamiltonian systems, which are the systems we are mostly dealing with in *rattle*, is essentially characterising this set of problems and is ultimately related to fundamental principles od physics as *Liouvilles' theorem* and the principle of energy conservation.

It seems therefore obvious to require that the *symplecticity* property of the exact solutions of Hamiltonian systems, should also be embodied and respected by the numerical integration methods.[6] That is, any numerical method Φ_h approximating the flow of the exact solution such that

[6] Ronald D Ruth. A canonical integration technique. *IEEE Trans. Nucl. Sci.*, 30 (CERN-LEP-TH-83-14):2669-2671, 1983

$$(q_{n+1}, p_{n+1}) = \Phi_h(q_n, p_n) \tag{B.34}$$

given any point (q_n, p_n), should be is a symplectic transformation. Any of the methods described above, both explicit and implicit are not symplectic independently from the order they could reach. None of the above methods can guarantee to respect fundamental characteristic of dynamical systems as the conservation of energy. This can be easily understood on the basis of the Euler methods recalling that the explicit Euler method would tend to expand the energy of the system (solutions grow in energy) thus the section of the phase space would grow in area while the implicit Euler method would tend to reduce it (solutions would tend to stability even of analytically they would not). This behaviour is depicted graphically in figure B.6 considering the example phase space flow generated by the Hamiltonian system of the simple pendulum.[7] The symplecticity request leads to the formulation of a new family of *symplectic methods* which guarantee conservation of energy and area when applied to the integration of a dynamical system. The first of these methods is the *symplectic Euler* method which can be equivalently expressed in two ways:[8]

[7] Ernst Hairer, Christian Lubich, and Gerhard Wanner. *Geometric numerical integration: structure-preserving algorithms for ordinary differential equations*, volume 31. Springer Science & Business Media, 2006

[8] Rene de Vogelaere. Methods of integration which preserve the contact transformation property of the hamiltonian equations. *Department of Mathematics, University of Notre Dame, Report*, 4:30, 1956

$$\begin{aligned} p_{n+1} &= p_n - h\frac{\partial H(q_n, p_{n+1})}{\partial q} \\ q_{n+1} &= q_n + h\frac{\partial H(q_n, p_{n+1})}{\partial p} \end{aligned} \tag{B.35}$$

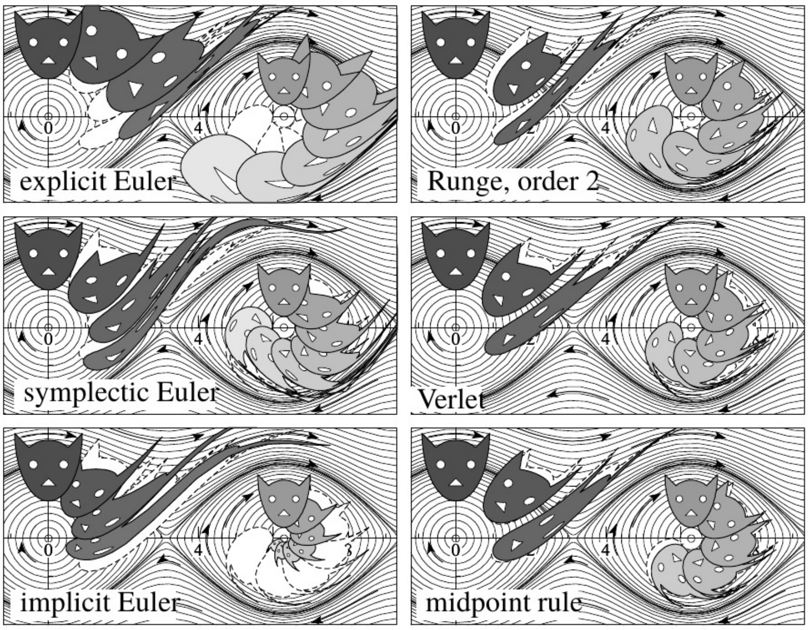


Figure B.6: Area preservation behaviour of various numerical integration methods on the basis of the a phase space of the simple pendulum. Same initial areas (and values) are chosen

or

$$p_{n+1} = p_n - h\frac{\partial H(q_{n+1}, p_n)}{\partial q} \tag{B.36}$$
$$q_{n+1} = q_n + h\frac{\partial H(q_{n+1}, p_n)}{\partial p}$$

which, recalling that:

$$-\frac{\partial H(q,p)}{\partial q} = -\frac{\partial U(q)}{\partial q} = f(q) \tag{B.37}$$

where $f(q)$ is the force acting on the mass and

$$\frac{\partial H(q,p)}{\partial p} = \frac{p}{m} = v \tag{B.38}$$

the former reduce to

$$p_{n+1} = p_n + hf(q_n) \tag{B.39}$$
$$q_{n+1} = q_n + h\frac{p_{n+1}}{m}$$

and the equivalent:

$$q_{n+1} = q_n + h\frac{p_n}{m} \tag{B.40}$$
$$p_{n+1} = p_n + hf(q_{n+1})$$

That is, each of these methods uses an implicit method for the evolution of one state variable and the explicit method for the other alternatively. The performance of these two methods, even if only of first order, is already much better in terms of stability as is depicted in figure B.7.

One of the most far reaching consequences of the *symplecticity* of Hamiltonian system, is that a geometrical way of thinking

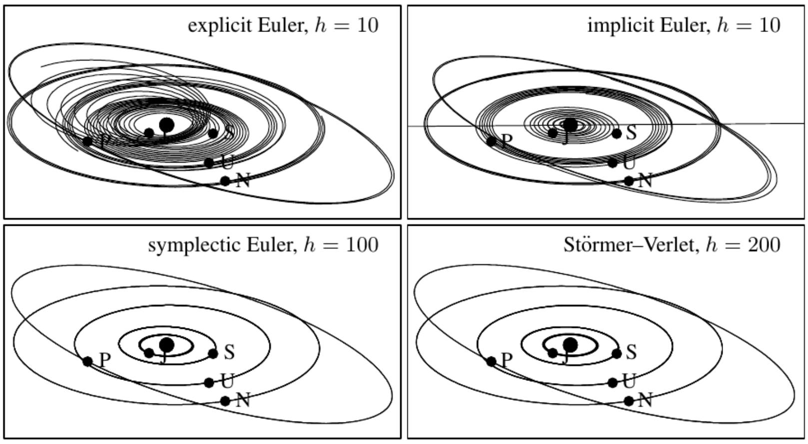


Figure B.7: Solution to the outer solar system as computed with the explict, implicit and symplectic Euler and the Strömer-Verlet methods. The graphic is taken for the previously cited book of E. Hairer: *Geometric numerical integration: structure-preserving algorithms for ordinary differential equations*

about the numerical integration of the evolution of such systems is made possible. In fact, these integration methods are usually also referred to as *geometric integrators*.

This geometric perspective is the basis of further development of those methods, given the following observations:

- *Composition*: Numerical methods can be composed in the same way functions can be composed. That is if Φ_h and Ψ_h are two different numerical methods of order r and s respectively for the same problem, their composition $\Phi_{\frac{h}{2}} \circ \Psi_{\frac{h}{2}}$ is also a method X_h for the same problem with order $r + s$.

- *Symmetry*: The exact flow of a dynamical system ϕ_t usually satisfies the relation $\phi_t^1 = \phi_t$: This property is in general not satisfied by the flow Φ_h of a numerical method. The *adjoint method* Φ_h^* is defined as equal to the inverse method with reversed time.

  $$\Phi_h^* = \Phi_{-h}^{-1} \qquad \text{(B.41)}$$

  and a method is called *symmetric* if is is equal to its adjoint $\Phi_h^* = \Phi_h$. Further, the adjoint of an adjoint method is the original method $(\Phi_h^*)^* = \Phi_h$ and the adjoint of a composition if the composition of the single adjoint methods in reversed order $(\Phi_h \circ \Psi_h)^* = \Psi_h^* \circ \Phi_h^*$. *Symmetry* is an important quality of flows which is related to the reversibility of dynamical systems, a fundamental characteristic of all conservative systems and is therefore a quality that a numerical method should provide.

- *Splitting*: A flow in phase space, i.e. a vector field, can be split into the sum of two (or more) simple flows along one of the dimensions of the phase space. The total flow is then the composition of the two flows (see figure B.8). For instance, the first symplectic

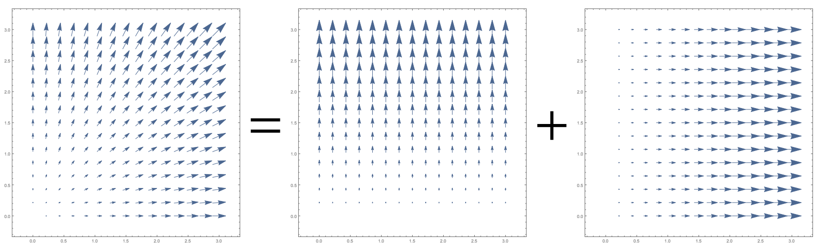


Figure B.8: The splitting of a flow in two dimensional phase space is expressed as the sum of two more simple flows

Euler method Φ_h formulated in equation B.40 could be split into two flows $\phi_h^{[1]}$ and $\phi_h^{[2]}$ respectively along the p and q dimensions:

$$\begin{aligned} &\phi_h^{[1]} \\ q_{n+1} &= q_n \\ p_{n+1} &= p_n + hf(q_n) \\ &\phi_h^{[2]} \\ q_{n+1} &= q_n + \frac{h}{m} p_n \\ p_{n+1} &= p_n \end{aligned}$$

so that

$$\Phi_h = \phi_h^{[1]} \circ \phi_h^{[2]} \tag{B.42}$$

Combining principles of *composition*, *symmetry* and *splitting*, a general rule of generation of symmetric symplectic methods of high order can be formulated[9]. As an example we look at the Euler method in equation B.40, split it in two flows, compose it with its adjoint and simplify thus obtaining:

$$\begin{aligned} \Phi^*_{\frac{h}{2}} \circ \Phi_{\frac{h}{2}} &= (\phi_{\frac{h}{2}}^{[1]} \circ \phi_{\frac{h}{2}}^{[2]})^* \circ (\phi_{\frac{h}{2}}^{[1]} \circ \phi_{\frac{h}{2}}^{[2]}) \\ &= \phi_{\frac{h}{2}}^{[2]} \circ \phi_{\frac{h}{2}}^{[1]} \circ \phi_{\frac{h}{2}}^{[1]} \circ \phi_{\frac{h}{2}}^{[2]} \\ &= \phi_{\frac{h}{2}}^{[2]} \circ \phi_{h}^{[1]} \circ \phi_{\frac{h}{2}}^{[2]} \end{aligned} \tag{B.43}$$

that is a symmetric method of second order order. The above equation may also be rewritten as:

$$\begin{aligned} q_{n+\frac{1}{2}} &= q_n + \frac{h}{2m} p_n \\ p_{n+1} &= p_n + hf(q_{n+\frac{1}{2}}) \\ q_{n+\frac{1}{2}} &= q_{n+\frac{1}{2}} + \frac{h}{2m} p_{n+1} \end{aligned} \tag{B.44}$$

which is also known as the *Strömer-Verlet method*.

By reapplying *composition* and *splitting* to the above equation B.43 higher-order symmetric integration schemed can be deduced. Furthermore, these methods, can be generalised and be applied to multi-dimensional dynamical systems where the flow of the system can be reformulated as a composition of simple flows along each dimension. For

[9] Gilbert Strang. On the construction and comparison of difference schemes. *SIAM Journal on Numerical Analysis*, 5 (3):506-517, 1968; and Robert I McLachlan and G Reinout W Quispel. Splitting methods. *Acta Numerica*, 11:341-434, 2002

instance for a n dimensional dynamical system governed by the flow Φ_h:

$$\begin{aligned}
\dot{x}_1 &= f_1(x_1, x_2, \ldots, x_n) \\
\dot{x}_2 &= f_2(x_1, x_2, \ldots, x_n) \\
&\vdots \\
\dot{x}_n &= f_n(x_1, x_2, \ldots, x_n)
\end{aligned}$$

can be reformulated as a splitting into n first order flows

$$\Phi_h = \phi_h^1 \circ \phi_h^2 \circ \cdots \circ \phi_h^n$$

and therefore, using the adjoint, a second order symmetric method would be:

$$\Phi^*_{\frac{h}{2}} \circ \Phi_{\frac{h}{2}} = \phi^n_{\frac{h}{2}} \circ \cdots \circ \phi^2_{\frac{h}{2}} \circ \phi^1_h \circ \phi^2_{\frac{h}{2}} \circ \cdots \circ \phi^n_{\frac{h}{2}} \tag{B.45}$$

which is the integration method I used in the second formulation of *rattle* for integrating arbitrary multi-dimensional dynamical systems. To formulate a fourth order symmetric and symplectic integration method of the above one would simply use again composition and write the method:

$$\Phi^*_{\frac{h}{4}} \circ \Phi_{\frac{h}{4}} \circ \Phi^*_{\frac{h}{4}} \circ \Phi_{\frac{h}{4}} \tag{B.46}$$

and etc. for higher orders.

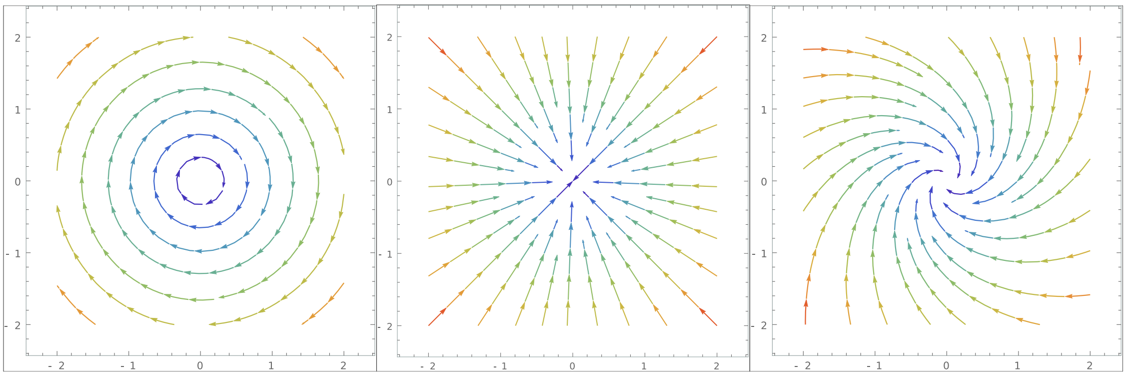
C
Phase space experiment

For this experiment a simple type of two dimensional dynamical system has been chosen, resulting in one of the most prototypical attractor types i.e. the centre attractor (the attractor of the simple harmonic oscillator). This dynamical system (DS in the following) produces a flow in the two dimensional phase plane which will induce each state, identified by the its values of the abscissa and ordinate of the plane, to vary and move when time advances: its evolution will inscribe trajectories accordingly to its specific attractor. The subsequent x and y coordinates a trajectory will traverse are assigned to salient characteristics of the output sound. In the following we have decided to use the value for controlling the *transposition* factor of the output's sound with the abscissa.

The involved performers are musicians who are asked to react to the sound produced by the computer music system by playing their instruments. The instrument's sound is picked up by a microphone, analysed and recorded: a contact microphone is used in order to allow the musician to move and to keep a coherent recording level throughout the experiment. Thus, *only sound* is used as input and output in this experiment i.e. no other sensing technology as motion tracking is employed.

A crucial element is of course exactly how the coupling between the performer and computer music system is formulated, that is, how the analysed sound of the musician influences the DS's evolution. In a first implementation the coupling has been understood as a second *perturbing* DS which modifies the unperturbed DS. The magnitude of of this system's influence is modulated in dependence of the input sound's features. This perturbing DS is a *node* type attractor. Exemplifying the effect of combining the two attractors, in figure C top row a centre attractor is perturbed with a node attractor with magnitude 1.0: the resulting attractor is the asymptotically stable inward spiral, in which the phase space trajectories spiral down towards the origin.

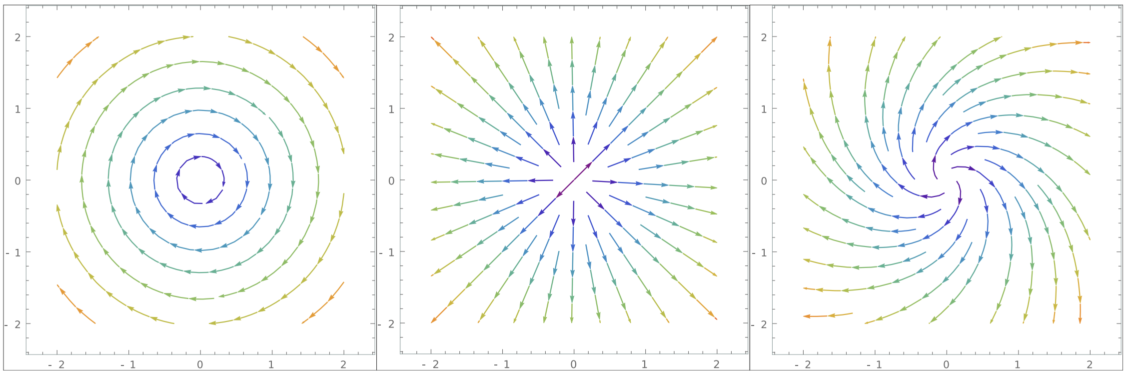
In figure C bottom row instead, the centre attractor is perturbed with a *source* i.e. a node attractor with magnitude −1.0: in this case the result is the asymptotically instable outward spiral, which causes trajectories to spiral out from the origin.



(a) Centre attractor

(b) Node perturbation with amplitude 1.0: *sink*

(c) Resulting attractor: inward spiral node



(d) Centre attractor

(e) Node perturbation with amplitude -1.0: *source*

(f) resulting attractor: outward spiral node

This DS could be expressed mathematically using the Jacobi matrices formalism with the following system:

$$\begin{pmatrix} \dot{x} \\ \dot{y} \end{pmatrix} = \left[\begin{pmatrix} 0 & a \\ -a & 0 \end{pmatrix} + p \begin{pmatrix} 1 & 0 \\ 0 & 1 \end{pmatrix} \right] \begin{pmatrix} x \\ y \end{pmatrix}, p \in [-1, 1] \qquad \text{(C.1)}$$

Here p is the perturbation's magnitude and a is the period of oscillation of the harmonic oscillator. As a first choice, this factor is chosen such that this time interval is at ca. $2.6s$, four times the maximal *salience of pulse sensation*, which lies approximately at $600ms$.[1] This choice would ensure that the musicians can easily hear the period of the inherent oscillation produced by the unperturbed DS. However, this value has been left variable in order to allow adjusting during the experiment.

In this experiment, the value of p has been made dependent on the input sound's instantaneous *RMS variation*. The RMS

[1] Richard Parncutt. A perceptual model of pulse salience and metrical accent in musical rhythms. *Music Perception: An Interdisciplinary Journal*, 11(4): 409-464, 1994

value is computed over a variable time window ranging from $10ms$ to $1s$. After having computed its variation, this value is scaled, mapped and clipped in the value range from −1.0 to 1.0 through a specialised sigmoid function.

To this end, the input signal s is written into a ringbuffer. Furthermore, the *RMS* of the current input signal $s[n]$ is computed using the following algorithm which allows for fast sample per sample calculation:

$$sumSquared[n] = sumSquared[n-1] - s[n - rmsSize]^2 + s[n]^2 \tag{C.2}$$

$$rms[n] = \sqrt{\frac{sumSquared[n]}{rmsSize}} \tag{C.3}$$

where *rmsSize* is the chosen RMS window size. Next the variation of the *RMS* with respect to its value *rmsDel* samples before is computed and passed through a sigmoid function:

$$drms[n] = sigmoid(rms[n] - rms[n - rmsDel], p, g) \tag{C.4}$$

where $rmsDel = 512$. The specialised sigmoid function is implemented using the formula:

$$sigmoid(x, p, g) = \left(1 + \frac{2}{exp(p) - 1}\right)\left(\frac{2}{exp\left(\frac{p|x|^g}{x}\right)} - 1\right) \tag{C.5}$$

which allows to have a small "gating" region around the origin in dependence of the factor g (see figure C.1). In this implementation $g = 3.0$ and $p = 7.0$.

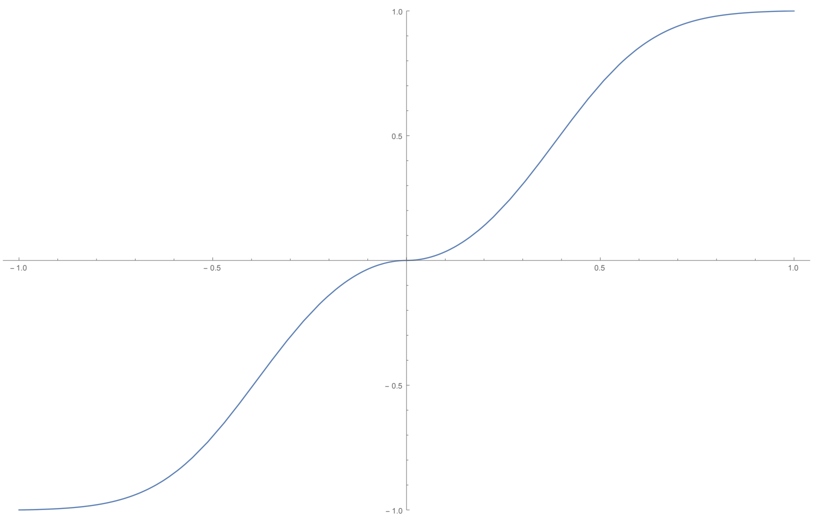


Figure C.1: specialised sigmoid function with $p = 7.0$ and $g = 3.0$

The value of $drms[n]$ is again smoothed using an integrator (also know as "lag" e.g. in the *SuperCollider* programming language) with a $0.1s$ seconds t_{60} time constant:

$$lagRms = exp\left(\frac{log\,10(0.001)}{10 * 44100}\right)$$

$$drmsL[n] = drms[n] + (drmsL[n-1] - drms[n]) * lagRms \quad \text{(C.6)}$$

and eventually rescaled to be used as the magnitude p of the attractor perturbation as in Equations C.1 and ??.

$$p = magPer * drmsL[n] \quad \text{(C.7)}$$

The parametrisations for the input signal conditioning stage have been chosen such that slow crescendi or decrescendi would have the maximum effect in perturbing the underlying attractor, whereas short or impulsive changes in the input signal's amplitude have a minimal impact on the evolution of the dynamical system.

More in detail, a constant crescendo leads to a constant positive derivative of the RMS. As this crescendo is slow the variation and thus the derivative will not be very big and its value would map in the linear positive region of the sigmoid. A fast change in the input RMS would lead to very high value returning to a very small value after a very short time. The subsequent integrator step would then minimise the effect even more.

In order to avoid that the state of the system would grow too large due to the perturbations, an additional flow field has been applied which would drag the current state towards the plane origin when its distance from it is greater then a certain threshold.

$$\mathbf{lim}(x,y) = \begin{cases} \begin{pmatrix} -1 & 0 \\ 0 & -1 \end{pmatrix} \begin{pmatrix} x \\ y \end{pmatrix}, & \text{if } r \geq thresh \\ \begin{pmatrix} 0 \\ 0 \end{pmatrix}, & \text{otherwise} \end{cases} \quad \text{(C.8)}$$

where $r = \sqrt{(x^2 + y^2)}$ is the state's distance to the origin and $thresh = 2.0$. Added to the flows resulting from the system as in equations C.1, this vector field would ensure that the state system would stay mostly within the region with $r \leq 2.0$ and not grow indefinitely.

The plane origin is a singular point for the both dynamical systems. Especially in the scenario of the centre attractor, once the state of the system reaches this point of asymptotic stability, it would be impossible for it to leave this position as the flow in this point, even with perturbation will always be $(0,0)$. In order to avoid this situation, which would eventually stop the evolution of the system, a second fixed flow field has been added to the attractor flows.

$$\mathbf{push}(x,y) = \begin{cases} \begin{pmatrix} rand() & 0 \\ 0 & rand() \end{pmatrix} \begin{pmatrix} x \\ y \end{pmatrix}, & \text{if } r \leq floor \\ \begin{pmatrix} 0 \\ 0 \end{pmatrix}, & \text{otherwise} \end{cases} \tag{C.9}$$

where $rand()$ stands for a random number between -1 and 1 generated anew at each frame and $floor = 0.03$.

Everything has been implemented in the Fortran version of the *rattle* framework centred around the idea of phase space construction or the geometrical representation of dynamical systems (see appendix B *rattle* integration algorithms).

Taking only the RMS input signal as parameter was a choice on the one hand motivated by a reduction of the experiment's complexity and on the other intended, to provide an intuitive and simple parameter for the performer: RMS should be tightly related to the felt effort or the intensity of the playing. All other choices made during the implementation phase of the experiment have been taken with the aim to offer the possibility to the musicians to actually find out how the system works and reacts to their play while interacting with it and then to actually consciously engage with it.

The sound produced by the computer music system and heard by the musician is generated using two models: The musician's instrument sound is recorded and played back with a short delay of $5s$ using granular synthesis. The sound is transposed according the DS state's abscissa value remapped exponentially in the range from 0.5 to 2.0 (i.e. ±1 octave transposition). Thus, the sound would both give information about the DS's state evolution and of the musician's input.

With the previous implementation of coupling, first informal tests showed that the system would be very difficult to cope with. In particular there was clear tendency of the system to grow in energy as interaction with the performer through the node type of attractor pushed the paths of the system towards bigger orbits. Also, if by a decreasing RMS variation the system was brought to states near the origin of the phase space, a substantial bigger effort was needed to bring the system again to a path which showed a more sensible evolution.

Therefore a different, simpler and more directly controllable implementation of the coupling was sought. This second implementation in terms of a Jacobi matrix formulation

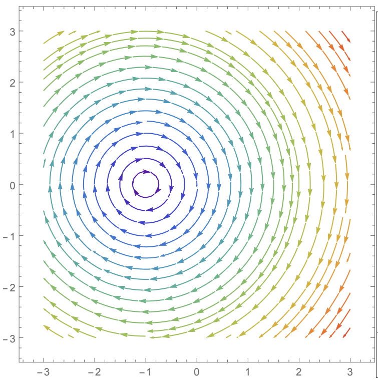
Figure C.2: Musicians Joel Diegert (left) and Lorenzo Derinni (right) while engaging with the phase space experiment setup.

could be written as:

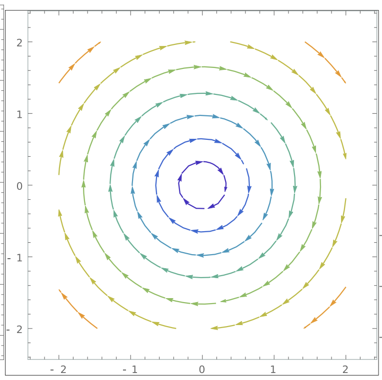
$$\begin{pmatrix} \dot{x} \\ \dot{y} \end{pmatrix} = \begin{pmatrix} 0 & a \\ -a & 0 \end{pmatrix} \begin{pmatrix} x \\ y \end{pmatrix} + \begin{pmatrix} 0 \\ p \end{pmatrix}, p \in [-1, 1] \tag{C.10}$$

where p remains the same as in the previous version.

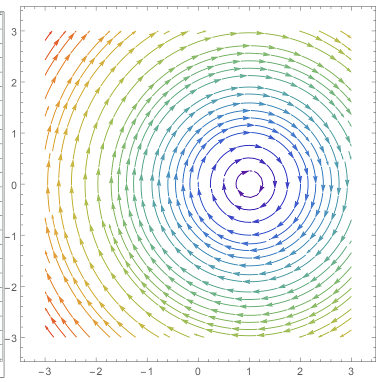
With this modification, a positive (increasing RMS) perturbation would "push" the current DS state towards the positive x axis, while a negative perturbation (decreasing RMS) towards the negative (see figure C). In addition, a weak attractor of node type has been added to the base DS, the effect of that would be a small but constant loss of energy of the system, which would then slowly



(a) Centre attractor perturbed according to equation C.10 with $p = -1.0$



(b) Unperturbed centre attractor



(c) Centre attractor perturbed with positive $p = 1.0$

spiral down towards the phase plane origin. That is, this attractor would act as a sort of "attrition" factor to the whole system. The magnitude of this attractor would be modulated with the system's state distance from the origin, so that attrition would be "turned off" when the system's own oscillations would be under a certain threshold. This means that the system would never "die out" (phase state at the phase plane origin) and always preserve some activity of its own.

As a consequence of these changes, on the one hand the performer could bring the system into resonance by applying the right "push" at the right moment during the system's evolution: i.e. producing an increase of the RMS when the system state is in the $x < 0.0$ half-plane or a decrease of RMS when the system is in the $x > 0.0$ region. On the other hand, with the action of the "attrition" factor, the system would prevent and non-controlled growth of its energy and continuously "digest" input energy while retaining a base amount of activity.

D
DBAP and ADBAP

In some of the works presented here, I make use of a simple algorithm to spatialise a sound source over a loudspeaker array of known positions. The algorithm is an extended and modified version of the *Distance Based Amplitude Panning* (DBAP) algorithm[1]. As this algorithm makes no *a priori* assumption of the effective loudspeaker setup and no assumptions as where the listeners are situated in the venue, also considering its relative low computational cost, this spatialisation method can be used very flexibly. It was therefore a natural choice when working with non-standard speaker distributions which are necessary in spaces where predefined speaker layouts cannot be applied or, as in some of the works I present here, the speaker layout itself becomes part of and artistic endeavour.

[1] Trond Lossius, Pascal Baltazar, and Théo de la Hogue. Dbap-distance-based amplitude panning. In *Proceedings of the Internatinal Computer Music Conference*, pages 489-492, 2009

The method is a panning algorithm modulating the amplitude a_i by which a sound source is projected in inverse dependence of the Cartesian distance d_i of the (virtual) sound source s to the a loudspeaker i.[2]

[2] Although original formulation of the method bases on a two-dimensional spatial representation of source and loudspeaker positions the extension implements a a three-dimensional version.

$$a_i = \frac{k}{d_i^p} \tag{D.1}$$

where p is an exponent coefficient calculated from the rolloff R in Decibels per doubling of distance

$$p = \frac{R}{20\,log_{10}2} \tag{D.2}$$

Setting $R = 6dB$ equals to the inverse distance law for free-field sound propagation.

Extending the principle of constant intensity stereo panning, the original DBAP method assumes that overall intensity is constant over the whole array regardless of the virtual source's position and therefore the sum of all squared amplitudes should be normalised to 1.

$$\sum_i a_i^2 = 1 \tag{D.3}$$

and the factor k in equation D.1 is then computed accordingly so that this normalisation holds.

$$k = \frac{1}{\sqrt{\sum_i \frac{1}{d_i^{2p}}}} \tag{D.4}$$

which also ensures that the loudspeaker amplitudes remain in the range $0 < a_i < 1$ for any distance, including $d_i = 0$.

Eventually, a *blurring factor* b is introduced in the calculation of the distances in order to adjust for too sharp changes in the amplitude distribution, i.e. the spatial spread when some $d_i = 0$. If (x_s, y_s, z_s) is the three dimensional position of the virtual sound source and (x_i, y_i, z_i) the position of the i loudspeaker:

$$d_i = \sqrt{(x_i - x_s)^2 + (y_i - y_s)^2 + (z_i - z_s)^2 + b^2} \tag{D.5}$$

that provides "smoother" variations around $d_i = 0$ (see figures D.1 and D.2).

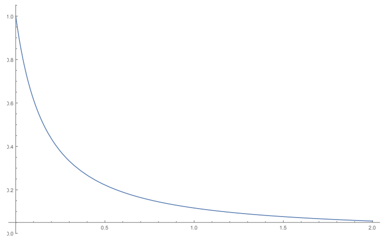


Figure D.1: one speaker DBAP amplitude as a function of distance without blur

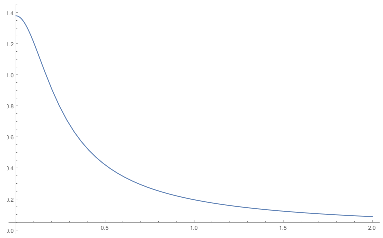


Figure D.2: one speaker DBAP amplitude as a function of distance with blur

Having specified the rolloff and blurring coefficients, the distances of the source to the associated loudspeaker objects are computed and used to determine the relative amplitudes of the projected sound. As a consequence of the implementation of the principle of constant intensity, positions outside the loudspeaker field cannot be clearly rendered: in this region the relative amplitude differences tend to zero with increasing distance while the overall intensity is still kept constant, resulting in a spatially undifferentiated sound output. The resulting overall intensity is constant, regardless of the position of the source.

In the course of our case studies, it turned out necessary to spatialise sources that could also travel out of the loudspeaker field and completely disappear. To achieve this, we modified the DBAP algorithm removing the constant intensity condition: sound spatialisation is achieved defining a distribution of absolute rather than relative amplitudes. This causes sources that move sufficiently far away from the loudspeaker array to fade out. Furthermore, the trajectory of moving sounds appears more clearly shaped or "sharper", compared to the unmodified DBAP algorithm. Lacking a more explanatory name, we call this simplified version of the DBAP algorithm *Absolute Distance Based Amplitude Panning* (ADBAP).

Using the "blurred" distance introduced in equation D.5, the ADBAP would then compute the amplitude of the i-th loudspeaker as:

$$a_i = \left(\frac{b}{d_i}\right)^p \tag{D.6}$$

which ensures that $0 \leq a_i \leq 1$ for any distance. In this case, one can imagine the effect of the blur as a sort of source widening; still the ADBAP would provide the "correct" behaviour of the loudspeaker amplitudes with respect to the inverse distance law. In fact the slope of the amplitude function D.6 is proportional to the derivative of the same function without blurring function: that is, the variations in distance would produce similar variations in both cases, in particular for distances $d_i \gg b$. This is particularly important for moving sound sources, which is the case in most of the works I refer to here.

Figure D.3 shows the slope of the function D.6 for different blur factors.

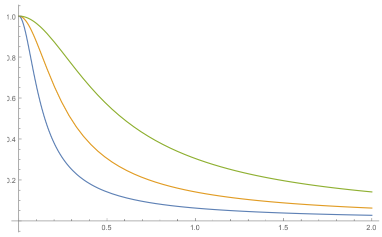


Figure D.3: Behaviour of the function D.6 in dependence of the distance d_i for different blur factors: b = 0.1 corresponds to the blue function, b = 0.2 to the orange and b = 0.4 to the green

E

Own Publications

I collect here a list of the research I've worked on and that has been published in the course of this dissertation.

D Pirrò. Staging collisions: On behaviour. In Michael Schwab, editor, *Transpositions*, number 1 in Aesthetico-Epistemic Operators in Artistic Research. Leuven University Press, forthcoming in 2018.

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