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Unconventional Computing and Music: An Investigation into Harnessing *Physarum polycephalum*

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This thesis is dedicated to my Nan, Christine Braund, who sadly passed during my time as a Ph.D. student.

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There are a lot of horror stories out there about life as a PhD student. Fortunately, my time was quite the opposite. I have been lucky enough to have an inspiring and hugely supportive supervisory team. I have been a member of a dynamic and innovative research group that contains some of my best friends. I would say my experience at the ICCMR has been nothing short of exemplary. Furthermore, it is important to express that Plymouth University has provided me with an enormous amount of support by awarding me with a studentship that allowed me to concentrate purely on my research. The Lovelace trust has also been very supportive by generously awarding me with grants.

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Finally, in the words of my good friend and former colleague Joel Eaton: Jared, *"get on with your PhD!"* (1, p.xviii).

Declaration

At no time during the registration for the degree of Doctor of Philosophy has the author been registered for any other University award without prior agreement of the Graduate Committee. Work submitted for this research degree at Plymouth University has not formed part of any other degree either at Plymouth University or at another establishment.

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Abstract

This thesis presents an investigation into developing musical systems with an Unconventional Computing substrate. Computer musicians have found it difficult to access the field of Unconventional Computing, which is likely due to its resource-intensive and complex nature. However, ongoing research is establishing the myxomycete *Physarum polycephalum* as a universally-accessible and versatile biological computing substrate. As such, the organism is a potential gateway for computer musicians to begin experimenting with aspects of Unconventional Computing. *Physarum polycephalum*, in its vegetative plasmodium form, is an amorphous unicellular organism that can respond with natural parallelism to the environmental conditions that surround it.

This thesis explores the challenges and opportunities related to developing musical systems with *Physarum polycephalum*. As this area of inquiry is in its infancy, the research took inspiration from a common approach in Unconventional Computing: a journey of exploration and discovery. This journey consisted of a selection of waypoints that provided direction while allowing the research to explore applications of *Physarum polycephalum* in order to establish how it may be useful in Computer Music. These waypoints guided the research from adapting established prototypes for musical application to developing purpose-made musical demonstrators for use outside of the laboratory. Thus, the thesis reports on a series of Computer Music systems that explore one or more features of *Physarum polycephalum's* behaviour and physiology. First, the text presents an approach to algorithmic composition that exploits the organism's ability to form and reconfigure graph-like structures. Next, the thesis reports on systems that harness the plasmodium's electrical potential oscillations for sound synthesis and compositional tools. Finally, the thesis presents musical devices that encompass living plasmodium as electrical components. Where applicable, the thesis includes artefacts from demonstrations of these systems, some of which were developed in collaboration with a composer.

The findings from this journey demonstrate that *Physarum polycephalum* is an appropriate substrate for computer musicians wanting to explore Unconventional Computing approaches creatively. Although *Physarum polycephalum* is relatively robust as a biological substrate, several obstacles arose during this project. This research addressed such obstacles by reviewing and selecting approaches that maintained the organism's accessibility to computer musicians. As a result, the work suggests methods for developing systems with the organism that are practical for the average music technologist and also beneficial to the wider group of scientists investigating *Physarum polycephalum* for other purposes.

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Glossary

AISB	Society for the Study of Artificial Intelligence and Simulation of Behaviour
ATP	Adenosine Triphosphate
BPM	Beats Per Minute
Ca^{2+}	Calcium
CAMUS	Cellular Automata MUSic
ChaoSynth	Chemical Oscillator Synthesiser
CM	Computer Music
cm	Centimeters
CSIR	Council for Scientific and Industrial Research
DAC	Digital-to-Analogue Converter
DAW	Digital Audio Workstation
EDVAC	Electronic Discrete Variable Automatic Computer
EL	Electroluminous
FFT	Fast Fourier Transform
GoL	Game of Life
GS	Granular Synthesis

HIPS	High Impact Polystyrene
HP	Hewlett-Packard
I	Current
ICCMR	Interdisciplinary Centre for Computer Music Research
ICUC	International Center of Unconventional Computing
ILLIAC	Illinois Automatic Computer
K^+	Potassium
KU	Kolmogorov-Uspensky
MEA	Multielectrode Array
MIDI	Musical Instrument Digital Interface
mL	Millilitre
mm	Millimeters
MRP	Magnetic Resonator Piano
mV	Millivolts
Na^+	Sodium
NADH	Nicotinamide Adenine Dinucleotide in reduced form
NADPH	Nicotinamide Adenine Dinucleotide Phosphate in reduced form
P. polycephalum	Physarum polycephalum
PDMS	Polydimethylsiloxane
PEDOT:PSS	Poly(3,4-ethylenedioxythiophene) Polystyrene Sulfonate
PLA	Polylactic Acid
PVC	Polyvinyl Chloride

QC	Quantum Computer
Redox	Reduction-oxidation reaction
STDP	Spike-Timing-Dependent Plasticity
UC	Unconventional Computing
UWE	University of the West of England
V	Voltage

1

Introduction

1.1 Chapter Overview

This first chapter begins by briefly introducing the thesis's subject area and remit. Next, it details the research's motivations interlinked with the author's background story. This section allows the reader to understand the background layer from which this thesis emerged along with the author's dispositions. Next, the research methods and questions are detailed. The chapter also documents the thesis's structure and related publications.

The structure of this chapter is as follows:

- 1.2 - Introduction
- 1.3 - Motivations
- 1.4 - Research Methods and Questions
- 1.5 - Thesis Structure
- 1.6 - Publications

1.2 Introduction

> *"...the history of computer music is also the history of computing because hardware and software developments in the computing world directly affected the computer music world."* (6, p.49)

Computer musicians, perhaps more than any other discipline-specific group in the arts, have always looked to technology to enhance their metier. Indeed, in Computer Music (CM), we have a rich history of experimenting with obscure and emerging technologies. Such technological curiosity extends back to the field's genesis where computer scientists in the 1950s manipulated the architectures of the early computing machines to play renditions of popular songs (7). Since these playful experiments, the field of music has remained tightly interlaced with the computer. Subsequently, music is an inherent beneficiary of advances in Computer Science and hardware (6). For example, the development of the Digital-to-Analogue-Converter (DAC) gave us advanced computer sound synthesis and the internet gave us mass non-tangible distribution of music. Today we have dedicated research laboratories that spend a great deal of time harnessing the latest in technological advances for music. As a result, we have musical systems that take advantage of cutting-edge developments in fields such as neuroscience, where computing systems can detect a user's emotions and play music accordingly (8), to cite but one example. Therefore, it is likely that developments in technology will continue to have a profound impact on the field of music.

Nowadays computers and electronic devices are ubiquitous and essential to the functioning of our society. Such devices are capable of performing processes that would have been unthinkable a century ago. Despite its incredible abilities, we are in constant pursuit of advancing technology. Our desire for progress here has increased the visibility and research momentum of Unconventional Computation (UC), with research laboratories forming that are primarily committed to such a pursuit. Researchers in the field of UC look to develop novel computation, sensing, and actuating systems inspired by or using the information processing abilities of biological, chemical, and physical systems. The aim of this field is to enrich or go beyond our current approaches to computation.

Given that computer musicians are inquisitive about technology, we would expect practitioners to show a keen interest in UC. Until recently, however, little cross-disciplinary investigations existed, which is potentially due to UC being dominated by theoretical research. In several instances, such research is surrounded by exciting perspectives but often not developed into prototypes. The reason for this lack of realisations may be explained by its dependency on the expertise of biologists, chemists, and physicists whose research interests reside elsewhere. In addition to UC's complex theoretical nature, the majority of prototypes that researchers have developed are inaccessible to the non-expert and general public. As Adamatzky explains: *"Unconventional Computing is chock full of theoretical stuff. There are just a handful of experimental laboratory prototypes. They are outstanding but difficult for non-experts to play with."* (9, p.v). Furthermore, those prototypes that do become commercialised are often unaffordable. For instance, D-Wave Systems, in Canada, has recently started to commercialise the world's first 'quantum computer', which is the size of a small room, takes several months to install, and only a handful of large corporations, such as Google in partnership with NASA, can afford to acquire. As such, the majority of developments from the field of UC are unrealistic for most investigators looking to explore their practical applications creatively. However, research over the past decade is suggesting there may be an accessible alternative.

The plasmodial slime mould *Physarum polycephalum*, henceforth known as *P. polycephalum*, is a biological computing substrate that requires comparatively fewer resources than most other UC prototypes. This organism is easy to look after, safe to use, and inexpensive to acquire and maintain. Such attributes are unique in UC and enable non-biologists to obtain and experiment with the organism. As a result, engineers and computer scientists have been able to implement sensing, actuating, and computing prototypes using living biological material. The amount of UC research into *P. polycephalum* has increased exponentially since its inauguration into the field in 2000 (10). Researchers have developed an impressively diverse and vibrant range of experimental prototypes exploiting the organism's information processing abilities. Such a span of experimental proofs has led to one *P. polycephalum* advocate describing the organism as the *"Swiss knife of the unconventional computing: give the slime mould a problem it will solve it"* (11, p.1). As *P. polycephalum* has made UC prototyping feasible for computer scientists and engineers, is it also a potential gateway for computer musicians? The time is ripe to explore and begin to understand if this emerging area of science holds potential for music.

1.3 Motivations

The ICCMR were exploring UC in music for a number of years before I became a member. Upon my joining in 2013, Professor Eduardo Miranda introduced me to the group's research in this area. He explained that the work was in pursuit of developing hybrid technology for CM. Their purpose here was to start building an understanding of how UC technologies may provide new pathways for music. This area of enquiry appealed to me above all of the ICCMR's other projects, which is likely a result of my keen interest in the development of novel and unusual music technologies.

At the time of my joining, the ICCMR's UC for CM investigation was wholly collaborative: they would focus on developing methods of producing musical/sonic artefacts using experimental data that science-based collaborators would gather. Furthermore, many of the projects harnessed materials that were out of reach for an average music technologist, which meant that it would be difficult to build upon their research or experiment with their approach. As a hands-on music technologist, I found this situation to be frustrating and, to a certain extent, counter productive. If research in this area was to provide a useful insight that engaged computer musicians, it must not only be concerned with breaking new ground. It should seek to entice and encourage computer musicians who are interested but hesitant to explore the potential of UC paradigms in their works due to the difficulty of finding schemes to adapt to their needs. These thoughts manifested into several questions. Is there a way to make UC accessible for computer musicians to experiment with outside of the laboratory? What form would a purpose-made musical UC system take? My eagerness to explore UC for CM to answer these questions became my primary motivation for completing this PhD.

As a music technologist with no formal science-based degrees, finding a UC substrate that allowed me to experiment independently was difficult. Fortunately, Professor Miranda lent me a book entitled *'Physarum Machines: Computers from Slime Mould'* that at the time was a recent publication by Professor Andrew Adamatzky (9). Within, the text talked on the accessibility constraints of UC and expressed that much of the research is out of reach to non-experts. The author went on to theorise that *"if there was a simple to maintain substrate, which requires minimal equipment to experiment with, then progress in designing novel computing devices would be much more* *visible”* (9, p.2). He then suggested that *P. polycephalum* is such a substrate and goes on to deliver an instructional guide for the UC novice on how to use the organism for computational purposes. This book provided me with two things. Firstly, it suggested that *P. polycephalum* may be an appropriate substrate for my research. Secondly, it served as a possible foundation for other CM practitioners who in the future may want to experiment with the outcomes of this study. Thus, *P.polycephalum* was my computing substrate of choice for this PhD research into UC for CM.

1.4 Research Methods and Questions

As stated in the previous section, before conducting this research there were only a handful of projects investigating aspects of UC for CM. The bulk of such projects were collaborations where the CM practitioners were not directly involved in the handling of the substrate. Rather, they were concerned with musically exploiting experimental data that was gathered by the collaborator. As such, instead of developing purpose made CM prototypes, many of the investigations used setups derived from previous experiments that they re-purposed for the CM project. This is likely the reason why the majority of the work involved sonification —the art of mapping data into sound —models with no real method of real-time or offline interaction. As a result, the outcomes were often single unique artefacts that offered little knowledge on the types of CM applications that may benefit from aspects of UC. No reusable tools or blueprints for musical devices were developed from these research progresses, and they did not begin to establish how CM may benefit from certain aspects of UC. This state of play made it difficult at the proposal stage to frame the research in terms of goals, aims, and outcomes. I did not know at this point what my end result would be, how it would be useful, and what methods I would need to adopt. The purpose of the research was to explore UC in CM in order to answer these types of questions.

1.4.1 The Journey Metaphor

In 2006 a large group of computer scientists collaborated to produce two papers in response to the UK Computing Research Council's call for grand challenges in Computer Science (12, 13). These papers put forward a case for research into non-classical computation fulfilling the grand challenge criteria. Within, the scientists discuss in excellent detail how they believe we should approach research into non-classical, or unconventional, computation. They talked about how the metaphor of a journey is much more compatible with this type of investigation than the conventional approach of setting goals. Their rationale here is that goals are fixed endpoints that influence the route taken to it. Journeys of discovery, however, are much more open, and the research's endpoints are not pre-defined. Therefore, the emphasis is on the whole research process instead of focusing mainly on the final outcome. They explain:

> *"Journeys and goals have rather different properties. A goal is a fixed target, and influences the route taken to it. With an open journey of exploration, however, it is not possible to predict what will happen: The purpose of the journey is discovery, and the discoveries along the journey suggest new directions to take. One can suggest starting steps, and some intermediate way points, but not the detailed progress, and certainly not the end result."* (12, p.6)

As UC for CM is very much in its infancy, the metaphor of a journey with Waypoints is useful. It provides a way of directing the research to develop UC prototypes that conform to some basic criteria that the CM community expect from their technology while not forcibly directing progress in a certain direction. In regards to this research specifically, it puts the emphasis on the whole research process. Thus, aspects such as a music technologist's ability to handle and culture the organism are as important as developing the UC system and the musical result. Moreover, a journey allows for *P. polycephalum* to be immersed into application in order to build an appreciation of how UC may be useful for CM. The next section lays out this research's Waypoints and research questions.

1.4.2 Waypoints and Research Questions

This research consisted of five journey Waypoints that directed the investigation towards answering four research questions. These questions where postulated with the project's exploratory nature in mind and were derived from the motives discussed in Section 1.3.

Waypoints

- **Waypoint 1** - Ascertain *P. polycephalum* culturing methods.
    - Before any musical systems can be developed, it is necessary to acquire knowledge of how to handle and look after the organism. Thus, this first Waypoint directs the initial work towards gaining practical knowledge on how to culture the organism. Once the research has arrived at this Waypoint, the CM element of the investigation can begin.
- **Waypoint 2** - Adapt existing *P. polycephalum* prototypes for Computer Music.

  - Waypoint 2 is formulated to give the research traction by applying established approaches to developing prototypes with *P. polycephalum* to CM. This part of the research journey will provide means of developing an understanding of how the organism can be used in CM. It is likely that this process will yield both negative and positive insights. Both these insights are important to allow for the research to progress on to the next Waypoint.
- **Waypoint 3** - Establish how *P. polycephalum* may be useful for sound and music.
  - This Waypoint is concerned with reviewing the experience and knowledge gained from the previous Waypoint in order to establish which approaches to harnessing *P. polycephalum* may be useful for CM. This part of the journey funnels the research towards particular areas of CM where *P. polycephalum* may be well-suited.
- **Waypoint 4** - Develop purpose-made Computer Music systems.
  - With the knowledge provided by the previous Waypoint, it will be possible to drive the research towards developing a purpose-made CM system that takes best advantage of *P. polycephalum's* behaviour. Unlike the previous Waypoints, Waypoint 4 will be focused on a single CM application of the organism's behaviour.
- **Waypoint 5** - Develop purpose-made musical demonstrators for use outside of the laboratory.
  - Waypoint 5 is concerned with focusing efforts on developing the purpose-made CM system, produced through the previous Waypoint, into a demonstrator that can be used outside of the laboratory. This part of the research journey will address whether it is feasible to develop *P. polycephalum*-based music technology for real-world deployment.

Research Questions

- **RQ1**: How can *Physarum polycephalum* be used in Computer Music?
  - This first research question looks to build an understanding of how *P. polycephalum* might be used in CM. In the initial stages, addressing this question requires building an understanding of how other researchers have used

    the organism. Numerous prototypes have been developed that exploit the organism in different ways, a survey of these systems can be found in Chapter 2. By building an understanding of established approaches to harnessing *P. polycephalum*, the research can look to how such approaches may be applied to CM applications. This starts the learning process of understanding what aspects of the organism's physiology and behaviour might be useful for CM and allows for experiments to begin. Research in the later stages of the investigation will draw on this knowledge to build purpose-made *P. polycephalum*-based music technology. This question will be answered by the whole research process.

- **RQ2**: Is it possible to use *Physarum polycephalum* for real-world Computer Music applications outside of the laboratory?
    - A lot of the established UC prototypes require delicate, time-consuming, and controlled setups that are impractical for applications outside of the laboratory. Furthermore, in many cases, the UC prototype is not quick enough for live application and requires lengthy data collection processes. For many computer musicians, such constraints are likely to deter their interest in using UC. Therefore, this question investigates for methods to overcome these limitations in order to develop systems that computer musicians can use outside of a laboratory setting and in real-world applications such as live performance, for example. The question will be addressed by locating, evaluating, and selecting approaches to implementing *P. polycephalum* prototypes that are appropriate for computer musicians.
- **RQ3**: Is *Physarum polycephalum* an appropriate and practical substrate for research into Unconventional Computing for Computer Music?
    - UC is known for being complex and resource-intensive. This question will be addressed by reviewing the entire research process to suggest whether *P. polycephalum* is a good candidate for computer musicians who want to adopt UC substrates in their work. The question takes into account several aspects of the project. These include the organism's ease of maintenance, the robustness of the developed musical systems, the constraints of using

  and relying on biological material, the accessibility of the equipment required to prototype, and the opportunities of using *P. polycephalum* for CM. It also takes into account how well the research has disseminated and whether it captures the imagination and interest of the CM field and wider general public.

- **RQ4**: How can this research contribute to the general field of Unconventional Computing?
  - Both UC and CM are inherently interdisciplinary and benefit from advances in other fields. This project is primarily focused on how aspects of UC can be harnessed for CM. To this end, the research is conducted from the perspective and dispositions of a music technologist who is looking to solve CM-related problems. This question takes the opposite perspective to ascertain whether research with *P. polycephalum* for music can benefit the wider group of scientists and engineers investigating *P. polycephalum* for other UC purposes. To answer this question the challenges, opportunities, and subsequent methods that arise as a direct result of deploying *P. polycephalum*-based technology in a practical CM objective are reviewed to ascertain if they are also applicable elsewhere.

1.4.3 Methods

This PhD research was conducted within the Faculty of Art and Humanities, and, as such, was concerned with developing artistic applications with *P. polycephalum*. Thus, the core research domain was CM. However, as the project brought together two fields (CM and UC) that are both inherently interdisciplinary, the work presented in this thesis does address some of the relevant scientific and engineering issues related to harnessing *P. polycephalum* within technology. Therefore, the project harnessed a number of different research methods to ensure scientific rigour and creative freedom where appropriate. As a result, the outcomes of this research benefit both the CM community and the wider group of scientists investigating the organism for other purposes. Each of the specific methods are detailed where appropriate in the text.

In line with the journey approach, Chapters 4-6 present a body of work in chronological order. From the start, this investigation looked to adopt research methods that were accessible and appropriate for CM. Here, all software was programmed in Cycling 74's Max[1], which is a visual programming language that is widely used by the CM community. There was no need to obtain any special licences for the purchase and use of any of the biological supplies and electrical equipment used throughout this research.

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[1] `https://cycling74.com/`(Accessed: 13 November 2016)

1.5 Thesis Structure

This thesis is divided into 7 chapters, including this introduction chapter. The rest of the thesis is organised as follows:

Chapter 2 presents the reader with the necessary background information for understanding the thesis. First, the chapter presents a brief overview of relationship between computing hardware and the field of music. Next, the field of UC is introduced with some examples of prototypes and a discussion on the benefits and limitations of the field. Following on, the chapter focuses on the biological computing substrate *P. polycephalum*. Here, the organism's biology is detailed. Then, the notion of *'Physarum Machines'* is discussed along with a survey of projects that have exploited the organism for computing, sensing, and actuating. The chapter then concludes with discussions and a summary.

Chapter 3 is a survey of existing work into UC for CM. This chapter looks at the approaches other practitioners have used to harness UC systems for music. The purpose of this text is to present the current state of play in research towards harnessing UC for CM.

Chapter 4 documents the initial experimentation with *P. polycephalum*. First, the text focuses on experimental preliminaries. Here, methods of acquiring and culturing the plasmodium of *P. polycephalum* are presented. The second half of the chapter presents a series of three initial CM experiments that explore using established approaches to harnessing the organism for technology. In these experiments, *P. polycephalum* is deployed for algorithmic composition, sound synthesis, and within a musical step sequencer. The chapter concludes with discussions on the results and experienced gained from these initial works.

Chapter 5 reports on research into using *P. polycephalum*-based memristors for music. To begin with, the chapter introduces the memristor. Next, the text presents experiments that confirm findings that the protoplasmic tube exhibits memristive properties. Following on, a basic approach to encoding musical notes into voltages for a *P. polycephalum*-based memristor to process is detailed. The chapter finishes with discussions and an overview of the piece *BioComputer Music* which was composed using the presented technology.

Chapter 6 presents further development of the musical system detailed in the previous chapter. Firstly, methods to stabilise *P. polycephalum*-based memristors are introduced. Here, the design and testing of 3D printed receptacles are presented. These devices prove to significantly decrease growth time, increase lifespan, standardise component responses, and create a protected microenvironment to encapsulate the organism. The chapter then explores a new approach to encoding and decoding musical information for processing on *P. polycephalum*-based memristors. Next, the piece *BioComputer Rhythms* is discussed followed by conclusions.

Chapter 7 concludes this thesis by summarising the conclusions from each chapter against the research questions. The chapter also documents some areas for future research that are based on the findings presented in the preceding chapters.

1.6 Publications

The work documented in this thesis has resulted in several research publications, each of which are listed below.

- Braund, E. & Miranda, E. Music with unconventional computing: towards a platform for Physarum polycephalum sound synthesis. In *Computer Music Multidisciplinary Research (CMMR): Sound Music and Motion*, 142–149 (Marseille, France, 2013). **[Reports on work from Chapter 4, cited as (14)]**
- Braund, E. & Miranda, E. *Sound, music, and motion: 10th international symposium, CMMR 2013, Marseille, France, October 15-18, 2013. Revised selected papers*, chap. 11: Music with unconventional computing: a system for Physarum polycephalum sound synthesis, 175–189 (Springer, 2014). **[Reports on work from Chapter 4, cited as (15)]**
- Braund, E. & Miranda, E. Unconventional computing in music. In *Conference on Interdisciplinary Musicology (CIM14)*, 356–352 (Berlin, Germany, 2014). **[Reports on work from Chapter 3, cited as (16)]**
- Braund, E. & Miranda, E. *Evolutionary and biologically inspired music, sound, art and design: 4th international conference, EvoMUSART 2015, Copenhagen, Denmark, April 8-10, 2015, proceedings*, chap. 2: Music with unconventional computing: towards a step sequencer from plasmodium of Physarum polycephalum, 15–26 (Springer, 2015). **[Reports on work from Chapter 4, cited as (17)]**
- Braund, E., Sparrow, R. & Miranda, E. *Advances in Physarum Machines: sensing and computing with slime mould*, chap. 34: Physarum-based memristors for computer music, 755–775 (Springer, 2016). **[Reports on work from Chapter 5, cited as (18)]**
- Miranda, E. & Braund, E. *Advances in unconventional computing*, vol. 2, chap. 29: Experiments in musical biocomputing: towards new kinds of processors for audio and music, 739–761 (Springer, 2016). **[Reports on work from Chapters 4 and 5, cited as (19)]**

- Miranda, E. & Braund, E. Interactive musical biocomputer: an unconventional approach to research in unconventional computing. *Symmetry: Culture and Science* **28**, 7–20 (2017). **[Reports on work from Chapters 4 and 5, cited as (20)]**

- Braund, E. & Miranda, E. *Music, mind, and embodiment: 11th international symposium, CMMR 2015, Plymouth, UK, June 16-19, 2015. Revised selected papers*, chap. 26: BioComputer music: generating musical responses with Physarum polycephalum-based memristors, 405–419 (Springer, 2016). **[Reports on work from Chapter 5, cited as (21)]**

- Braund, E. & Miranda, E. *Music, mind, and embodiment: 11th international symposium, CMMR 2015, Plymouth, UK, June 16-19, 2015. Revised selected papers*, chap. 17: Music with unconventional computing: granular synthesis with the biological computing substrate Physarum polycephalum, 271–282 (Springer, 2016). **[Reports on work from Chapter 4, cited as (22)]**

- Braund, E. & Miranda, E. *Guide to unconventional computing for music*, chap. 8: An approach to building musical bioprocessors with Physarum polycephalum memristors, 219–244 (Springer, 2017). **[Reports on work from Chapters 5 and 6, cited as (23)]**

- Miranda, E., Kirke, A., Braund, E. & Antoine, A. *Guide to unconventional computing for music*, chap. 2: On unconventional computing for sound and music, 23–61 (Springer, 2017). **[Reports on work from Chapters 4, 5, and 6, cited as (24)]**

- Braund, E. & Miranda, E. On building practical biocomputers for real-world applications: receptacles for culturing slime mould memristors and component standardisation. *Journal of Bionic Engineering* **14**, 151–162 (2017). **[Reports on work from Chapter 6, cited as (25)]**

2

Background Information

2.1 Chapter Overview

This background information chapter has two purposes. Firstly, it aims to provide context and highlight the relevance of the forthcoming research by introducing the field in which this thesis is situated. Its second purpose is to present the reader with the background knowledge and key concepts surrounding the research.

To provide context to the research motives (Section 1.3), the initial section presents a historical overview of the computer's involvement and impact on the field of music. Here, I tell a brief story of the development of today's conventional computing machine interlaced with how such progress led to the genesis of CM. My rationale for including such a story is to explain to the reader how the pioneers approached using the early computing machines for sound/musical applications, which lays the groundwork for a survey of UC for CM in the next chapter.

Following on, Section 2.4 introduces the field of UC. Here, I define the field and its working methods and limitations. The chapter then focuses on the UC substrate that is central to this thesis: *P. polycephalum*. Firstly, a section introduces the organism's biology, which is followed by an overview of its involvement in UC. The chapter then concludes with discussions and a content summary. The structure of this chapter is as follows:

- 2.2 - Introduction
- 2.3 - The Computer and Music: Early Milestones

- 2.4 - Unconventional Computation
- 2.5 - *Physarum polycephalum*
- 2.6 - Physarum Machines
- 2.7 - Discussions
- 2.8 - Chapter Summary

2.2 Introduction

Computer Music, as a term, has its ambiguities. Keislar (26) suggests that it can be split into two meanings. The first is a musical genre where the computer plays some function in the realisation of the music and/or performance. The second is a technical discipline that looks to research, develop, and encompass aspects of the computer's abilities in music. This second definition is perhaps the oldest and highlights the intimacy between advances in Computer Science and musical possibilities. Composers and researchers who have approached innovations in computing technology with a creative mind have built a vast number of systems and artefacts that have played a pivotal part in the development of the music industry over the past 80 years. Thus, grand milestones in CM are bound to both advances in computing systems and the musical practitioners who engage with the latest technological breakthroughs.

2.3 The Computer and Music: Early Milestones

The notion of a calculating machine's musical potential first came from Ada Lovelace in the 19th century. Charles Babbage had asked Lovelace to write notes on the designs of his Analytical Engine (27): a mechanical general-purpose machine that is considered to be the precursor to today's computers (28). In these notes she expressed a perspective that the engine *"might compose elaborate and scientific pieces of music"* (29, p.1). Although her idea was never put into practice, it was published in a document that is considered to detail the first computing machine algorithms (30).

The first methods of actually producing musical sound with a computing machine is understood to have come from Alan Turing (the inventor of the Turing Machine (31)) during the late 1940s (32, 33). Here, Turing wrote manuals for the early Manchester/Ferranti family of computers (34, 35, 36). Within, he explained how to manipulate the machine's architecture to produce a middle C note and went on to discuss how programmers could create rhythms by producing machine sounds (35, p.24). Such techniques involved sending and delaying electrical impulses to a built-in loudspeaker. These instructions led to the first known audio recordings of CM (programmed by Christopher Starchily) in 1951. Around the same time, scientists in Australia were also looking into using the computer for music. Here, Geoff Hill programmed the CSIR Mk1 (37) to play a selection of popular melodies using similar techniques as Turing had suggested (7, 35). The musical experiments on these two computing machines (Ferranti Mark 1 and CSIR Mk1) are widely considered the genesis of CM. Their significance to music, however, is debated. These experiments, which mainly involved scientists and engineers, were tangential to the objectives the researches were funded to achieve (6). As such, composers were never invited to get involved and the musical activities were short-lived. It is important to note that at this time (late 1940s) computers were huge, immensely expensive, and required specialist knowledge to operate and maintain. Thus, they were not accessible to composers without collaborating with the very few organisations that had the machines.

It is acknowledged that the main ground breaking phase of CM began in the late 1950s with experiments in computer-assisted composition and computer-based sound synthesis (6, 7, 38).

Computer-assisted composition was initiated in the mid 1950s by Lejaren Hiller, a chemist with a musical background, and Leonard Isaacson, a mathematician (38). These two scientists were curious as to whether computer processes were capable of composing music (39). Their curiosity stemmed from a comparison between the computer's abilities and the process of composing:

> *"It is a feature of digital computers that they can be efficiently used to "create a random universe" and to select ordered sets of information from this random universe in accordance with imposed rules, musical or otherwise. Since the process of creative composition can be similarly viewed as an imposition of order upon an infinite variety of possibilities, an analogy between the two processes seems to hold."* (39, p.2)

To investigate their ideas, they collaborated to program the Illinois Automatic Computer (ILLIAC) to compose music for a string quartet (39). The *Illiac Suite* comprised four movements that were each a result of a different CM experiment. As the computer had no way of printing musical scores, Hiller and Isaacson had to transcribe the results of each of these experiments into notation by hand. Although the *Illiac Suite* is recognised as the first computer-composed piece of music, Iannis Xenakis was also running CM experiments at about the same time (40, 41). Xenakis, using an IBM 7090 computer, developed a set of stochastic music programs that investigated how the computer could be used as a compositional aid. *'ST/10 080262'* was the first piece to result from his efforts, which premiered in 1962 at IBM's French headquarters (38).

Computer-based sound synthesis was developed in the 1950s following Bell Laboratories' research into the feasibility of transmitting telephone conversations digitally (38). Max Mathews, who was developing methods to calculate and generate sound with a computer, built a basic sound generating program called MUSIC I (42), which harnessed a new piece of hardware known as the Digital-to-Analogue-Converter (DAC). The invention of the DAC gave Mathews the ability to convert digital information into analogue voltages. This piece of hardware provided the first means of variable sound synthesis (6). Although a big leap forward from the initial computer-generated sounds, MUSIC I could only produce one voice that was limited to a single triangle-wave function. It took another two attempts and the progression from valve technology to transistor-based circuits for his work to gain the interest of composers and engineers

(38). From 1957-1968, Mathews developed a whole series of MUSIC-N programs that continued to take advantage of developments in hardware and software (6, 43, 44).

Since these early milestones, the field of music has remained tightly interlaced with the computer, with advances in technology having a significant impact on both the way we consume and produce music. For example, today we have digital audio workstations (DAW) to compose music on, mass non-tangible distribution of music over the internet, and musical systems that can analyse a composer's repertoire and produce original material in a similar style (45). Computer musicians have even developed systems that are capable of continuing a musician's performance live once they have ceased playing (46).

The development of computing technologies over the past century is perhaps the most liberating period in the history of music. Thus, with mankind's ever-increasing pursuit of advancing science and its application in technology, the question of 'what is next for music?' arises.

2.4 Unconventional Computation

Today's electronic computers lay their ancestral roots with the Turing machine (31) and the Electronic Discrete Variable Automatic Computer (EDVAC) architecture (47) —also colloquially known as the von Neumann architecture —, which were postulated in the 1930s and 1940s, respectively. Over the past 80 years, these inventions have undergone exponential development and are an extraordinary success story. In today's technologically advancing world, the computer is ubiquitous. There is, however, an increasing consensus amongst computer scientists that we will soon reach the limit of today's conventional computing systems (12, 13, 48, 49). Our movement towards such a threshold is due to our ever-growing need for faster and more efficient technology, along with a pursuit for new kinds of computers to address problems that are arduous to address with current computing technologies. An example being self-organisation in non-equilibrium systems, to cite but one. Moreover, as Stepney et al. explain, conventional computation *"encompasses an extremely small subset of all computational possibilities"* (12, p.6). They go on to suggest that in Computer Science we have created unnecessary limitations and that *"we need to distinguish this has to be the case from the merely this has always been the case"* (12, p.6).

Our desire for progress here has, over the last decade, increased the visibility and research momentum of UC, with research labs forming that are primarily committed to such a pursuit. The field of UC looks to the information processing abilities of biological, chemical, and physical systems and how they may be exploited in either a genuine (i.e. using the real-world phenomena) or utopian (i.e. inspired algorithms) computational scheme. It is important to acknowledge that UC is, as Adamatzky puts it, *"an art of interpretation"* (9, p.vii). The world around us does not compute, it obeys the laws of physics, chemistry and biology. We can interpret the behaviour of natural phenomena as computation.

There is not a set criteria for classifying a computation scheme as 'unconventional'. As Adamatzky explains: *"What is unconventional computing? This is a matter of time scales, personal preferences and orthodoxy in education"* (50, p.1). We could define UC as anything that is not derived from the Turing Machine and EDVAC architecture. However, such a definition is only correct when considering today's point in time. Thus, I find words from Toffoli work best for defining the field through time: *"a* *computing scheme that today is viewed as unconventional may well be so because its time hasn't come yet-or is already gone"*(51, p.17). Thus, UC can describe a vast array of different technologies and theories. Some of the areas that are frequently explored in UC research are:

- **Biological-based computing** harnesses abstractions derived from biological systems to perform calculations by processing, storing, and retrieving data. The first implementation of computational technology materially based on biological concepts is believed to have been carried out by Adleman in 1994 (52). Since then, there has been a huge amount of interest in biological computing across disciplines. Examples include:
  - Biomolecular processors exploring the self-assembly properties of DNA (53).
  - Slime mould computing exploiting an amorphous organism's topology to find efficient pathways (9).
  - Information processing in microtubules (54).
- **Chemistry-based computing** explores encoding data as chemical concentrations in a solution. Chemical reactions represent the computation process and the subsequent concentration profiles of the reagents are the results. The first ever chemical processor prototype was developed in the mid-1980s by Kuhnert (55). Some examples of chemical computing include:
  - Reaction-diffusion chemical processors exploring interacting growing patterns, excitation, and diffusion waves (56).
  - Image processing using light-sensitive chemical reactions (57).
- **Physics-based computing** studies and develops theoretical computation models that make use of quantitative theories in physics. Our current computers fall into this computing category. Other examples are:
  - Quantum computing exploring the use of quantum mechanical phenomenon to represent and process data (58).
  - Analogue computing using and manipulating continuous values to model problems (59).

UC research into new types of systems tends to take a different approach to developing computing schemes than conventional computation. Here, as opposed to building the hardware and program around a pre-determined computing theory, everything is centred and built around the hardware/wetware (i.e. the real-world phenomena) (48). Arguably, this approach is more efficient as the hardware/wetware is not coerced into a computational model that does not naturally fit. Moreover, the theory is not established before the applications. This approach, however, is not conducive to universality, which is one of the key targets that scientists have focused on since Babbage's Analytical Engine (60). Universal machines make the most practical sense for the everyday user: most people would not want to have an individual machine for every different task. For example, different machines to type a document, spell check it, and email it. The aim of UC, however, is not necessarily to replace our conventional machines:

> *"forms of non-classical computation will not supersede classical computation: they will augment and enrich it. And when a wide range of tools is available, we can pick the best one, or the best combination, for each job"* (12, p.15).

There are several fruitful perspectives surrounding work in UC. For example, Stepney predicts that if the same level of development is mirrored in the advancement of new, unconventional, computation then the *"world of computation will be unrecognisably different from today"* (48, p.1947). However, one of the main obstacles to making progress is the field's accessibility to non-experts. Historically, UC has been dominated by theoretical research with very few actual realisations. The prototypes that have been implemented are excellent but often require expensive lab equipment, specialist handling, and a good grasp of complex underlying theory to implement and use. Therefore, they are likely to be unrealistic for the great majority of investigators who are interested in exploring practical applications of UC developments. Adamatzky explains that

> *"a weak representation of laboratory experiments in the field of unconventional computers could be explained by technical difficulties and costs of*

> *prototyping. Chemists and biologists are not usually interested in experimenting with unconventional computers because such activity diverts them from mainstream research in their fields. Computer scientists and mathematicians would like to experiment but are scared of laboratory equipment.*
>
> *If there was a simple to maintain substrate, which requires minimal equipment to experiment with, then progress in designing novel computing devices would be much more visible.* (9, p.2)

Research over the past decade is suggesting that the plasmodial slime mould *P. polycephalum* may be a potential gateway for the non-expert to experiment with aspects of UC. Uniquely, this biological computing substrate requires comparatively fewer resources than most other substrates. The organism is cheap, openly obtainable, considered safe to use, and has a robustness that allows for ease of application (9). Moreover, as a result of such unique accessibility for a biological computing substrate, an instructional book on how to use the organism for computational purposes has been published for the UC novice (9). As the research motives in Section 1.3 elicit, recent progress with *P. polycephalum* has exemplified its versatility and accessibility, which is why it is the candidate for this investigation into UC for CM.

2.5 *Physarum polycephalum*

This section presents an introduction to the organism *P. polycephalum*, which belongs to the order *Physarales*, subclass *Myxogastromycetidae*, class *Myxomycete*. The purpose of this introduction is to provide the reader with a general knowledge of the organism's life cycle and biology. Such information gives context to the behaviour that developers exploit to implement UC systems with *P. polycephalum*. It also offers an introduction to some of the biological processes that are explored in the experimentation presented in later chapters.

2.5.1 Life Cycle

In the wild, the *P. polycephalum* passes through a complex life cycle that sees it develop from spore germination to sporangium (Figure 2.1). This lifecycle can be observed in culture in the laboratory. In one of its life cycle phases that is unique to the *Myxomycetes* (61), and the phase that is of relevance to this research, *P. polycephalum* exists as a large yellow mass of protoplasm that moves like a giant amoeba forming networks of protoplasmic tubes. During this vegetative plasmodium phase (Figure 2.1 step 10), the organism is amorphous, unicellular, and normally found in dark and high humidity environments. Although unicellular, plasmodia are visible to the unaided human eye. *P. polycephalum* can live as plasmodium for a considerable amount of time if it resides in favourable temperatures with a good supply of food. Daniel and Rusch (62) have developed methods that supposedly allow the plasmodium to be kept indefinitely. In their experiments they cultured the organism on a partially defined soluble medium for over four years without a decrease in growth rate. However, if the organism resides in environments with low temperatures and levels of humidity, and/or a lack of nutrients, it will attempt to migrate to find better conditions. If unsuccessful, the plasmodium enters its dormant sclerotium phase by forming a hardened mass (Figure 2.1 step 11). Sclerotia are highly resistant structures that are formed through the gradual desiccation by a *Myxomycete* (63). Structurally, sclerotia are *"nucleated spherules of cytoplasm enclosed within a honey-comb-like matrix of organic walls"* (64) (Figure 2.2). The sclerotium of *P. polycephalum* remains robust in conditions that are detrimental to vegetative growth. For example, Blackwell et al. (65) demonstrated that a *P.*

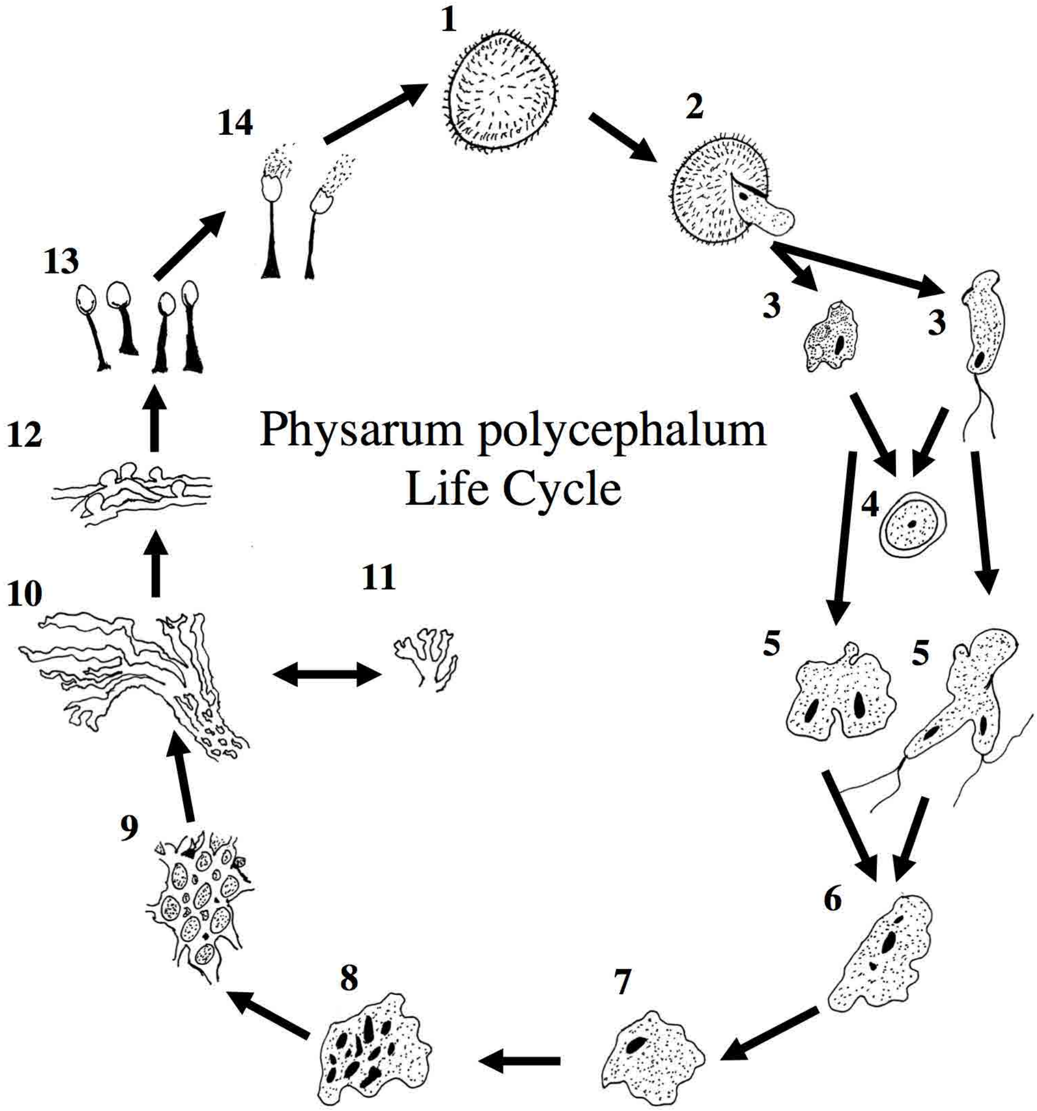

Figure 2.1: An illustration of *P. polycephalum's* life cycle generalised into 14 stages. 1—2 show spore and spore germination. 3 is a uninucleate phase where the cell may exist with (right) or without (left) a flagella. Stage 4 is a microcyst. Stage 5 to 6 is the joining of two compatible myxamoebae or swarm cells to produce a single cell. 7 is a Zygota and 8-9 is the early forming of plasmodium. 10 is a mature plasmodium that can form sclerotium, 11. 12 is the plasmodium beginning to form sporangia. 13 is mature sporangia, and, finally, 14 is the release of spores from the sporangia. This Figure is a drawing by the author that is inspired by an illustration from (2, p.287).

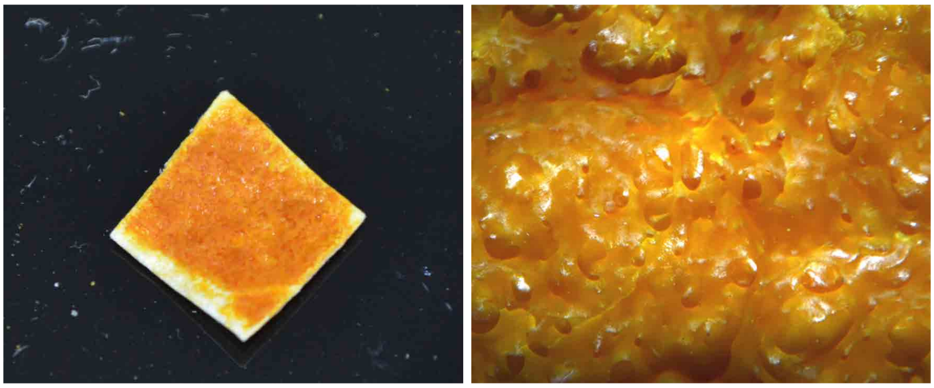

Figure 2.2: Pictures of a sclerotium of *P. polycephalum*. The left picture shows a sclerotium formed on filter paper: this is a common way that biological suppliers distribute specimens of the organism. The picture on the right shows the same filter paper but under 15x magnification. Here, the honey-comb-like matrix is clearly visible.

polycephalum sclerotium can survive for up to 32 days while exposed to a temperature of 60°. Furthermore, in (66) Luyet and Gehenio recorded a 50% survival rate with a *P. polycephalum* sclerotium at temperatures as high as 90°. From this dormant state, the organism can become plasmodium once more in the presence of moisture. Often, plasmodium of *P. polycephalum* is distributed by biological suppliers as sclerotium with instructions to reactivate it with a few drops of distilled water or on an agar substrate.

When deprived of nutrients and exposed to bright light, as opposed to forming sclerotium, the plasmodium forms fruiting bodies named sporangia (Figure 2.1 step 12-13). Moreover, as a survival mechanism, the plasmodium will form sporangia if the immediate environment becomes foul with bacteria. These structures take the form of tiny stalks with small enclosures on top that are full of spores (Figure 2.3). Nuclei in the sporangia undergo meiosis, subsequently filling the enclosure with many haploid spores. Upon the fruiting bodies drying out, a network of elastic fibres called capillitium expand causing the fruiting body to rupture, thus distributing the spores which can remain dormant for substantial durations of time (Figure 2.1 step 14). Spores germinate in wet conditions, releasing a unicellular myxamoebae of different mating strains. Such myxamoebas proliferate into microcysts, differentiate into flagellated swarm cells, or, if enough cells are present, they fuse to form a zygote. The zygote then undergo several instances of mitotic division to form the multinucleate plasmodium (see (67) for an extensive explanation of *P. polycephalum's* lifecycle).

Figure 2.3: Sporangia of *P. polycephalum*.

Throughout this thesis, the name *P. polycephalum* is used to refer to the organism in its plasmodium phase.

2.5.2 Plasmodium of *Physarum polycephalum*

The *P. polycephalum* species of plasmodium belongs to the type *Phaneroplasmoidum*, which is characterised by its large size (reaching up to meters in size) and morphology of networks of protoplasmic tubes laid down by a propagating fanlike structure of pseudopods (68) (Figure 2.4). During its vegetative state, *P. polycephalum* is an active mass of protoplasm with no cell wall that propagates at speeds of 1-5cm/hr (68).

Structurally, plasmodia's cytoplasm is comprised of two parts, the ectoplasm and the endoplasm (69). The ectoplasm is a semirigid tube-like cytoskeleton coated in a layer of protective slime material, the Glycocalyx, which gives rise to plasmodia informally being known as 'slime mould'. Within the cytoskeleton resides a network of actin-myosin filaments that rhythmically contract longitudinally, radially, and spirally (68, 70). Inside the ectoplasm there is a fluid cytosol endoplasm containing components such as nuclei, proteins, vacuoles, water with dissolved ions (e.g. Ca^{2+}), and various other organelles (69, 71). Plasmodia have a myriad of nuclei that undergo mitosis in synchrony approximately every 8-10 hours (61). Furthermore, if two plas-

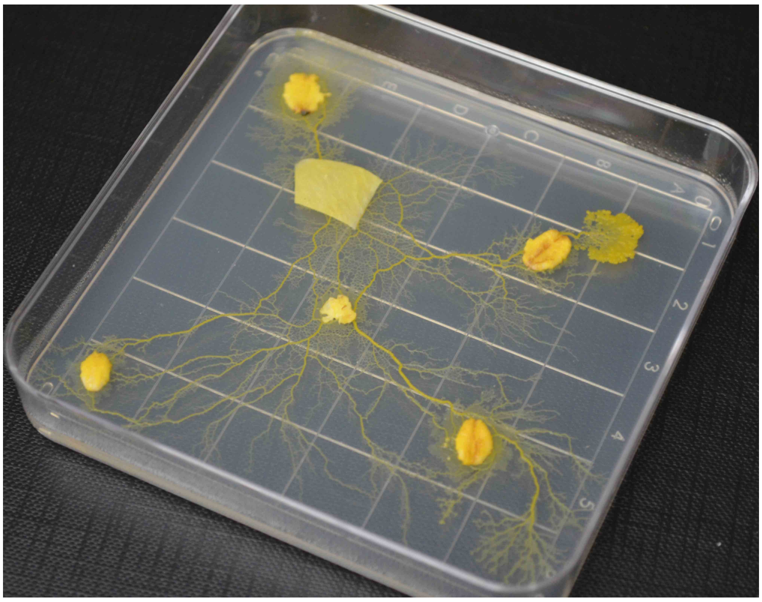

Figure 2.4: A photograph of a two-day old culture of plasmodium of *P. polycephalum*.

modia cells come into contact, they will coalesce and their mitosis cycles will become synchronised (72, 73, 74).

The contraction behaviour of the cytoskeleton causes pressure gradients to build up internally, resulting in the locomotion of the endoplasm (75). Such locomotion, known as shuttle streaming, serves as a circulation system for the cell, transporting nutrients, oxygen, and other elements in the endoplasm throughout the plasmodium (76). Shuttle streaming is a type of cytoplasmic streaming that is characterised by the rhythmic back-and-forth movement of the endoplasm. Visually, a propagating plasmodium has two distinct parts: an anterior of pseudopods forming a fanlike structure and a posterior of interconnected protoplasmic tubes (Figure 2.5). At the posterior, the ectoplasm constricts forcing the endoplasm to flow towards the anterior. Upon the endoplasmic flow decreasing in the direction of propagation, the anterior begins to constrict thus reversing the direction of flow. As propagation occurs, tubes are progressively sealed off with the partial solation of the ectoplasm (68). That is, ectoplasm is transformed into endoplasm and transported. Such activity causes higher net gradients of internal pressure to build up in the direction of propagation. The force of the streaming endoplasm builds in the anterior causing microtubules to form, which opens the anterior into a fanlike shape of forward-moving pseudopods (Figure 2.6). Shuttle streaming in

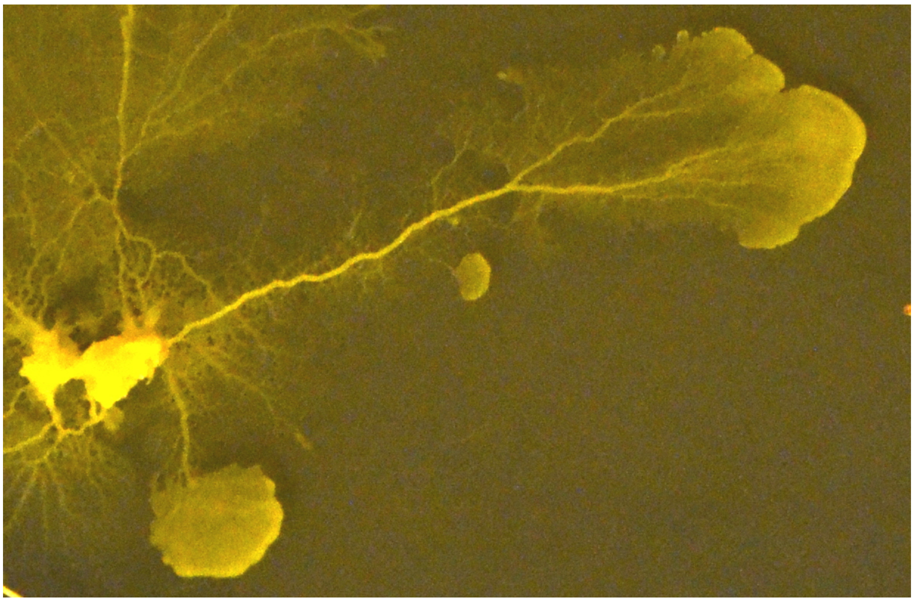

Figure 2.5: Fanlike shapes of forward-moving pseudopods laying down networks of protoplasmic tubes.

plasmodia can transport endoplasm at velocities of up to 1.3mm/s (77), switching polarity at intervals ranging from a few seconds to a few minutes with an average interval of approximately 1.3 minutes (75).

The plasmodium, although without a brain or serving centre of control, responds to the environment around it. Plasmodia propagate on gradients of attractant and repellent stimuli and feed on micro-particles and creatures such as bacteria and spores through a specific form of endocytosis called phagocytosis. Nakagaki et al. experimentally demonstrated that over time the organism optimises the topology of its protoplasmic network, increasing its harvesting and intracellular flow efficiency (78). The organism's ability to self-organise according to its local environment has given rise to its behaviour being labelled by some as 'intelligent' (79). The mechanisms behind such behaviour are still not completely understood. However, we know that positive and negative taxes correlate to actin-myosin relaxation and contraction (80).

Cytoskeleton contraction-relaxation cycles are not static; they are of different frequencies and phases in different regions of the organism (81). These cytoskeleton contraction rhythms are coupled with spatially distributed biochemical oscillations (e.g. ATP, H^+, NADH and Ca^{2+} (82, 83)) that have the ability to become synchronised

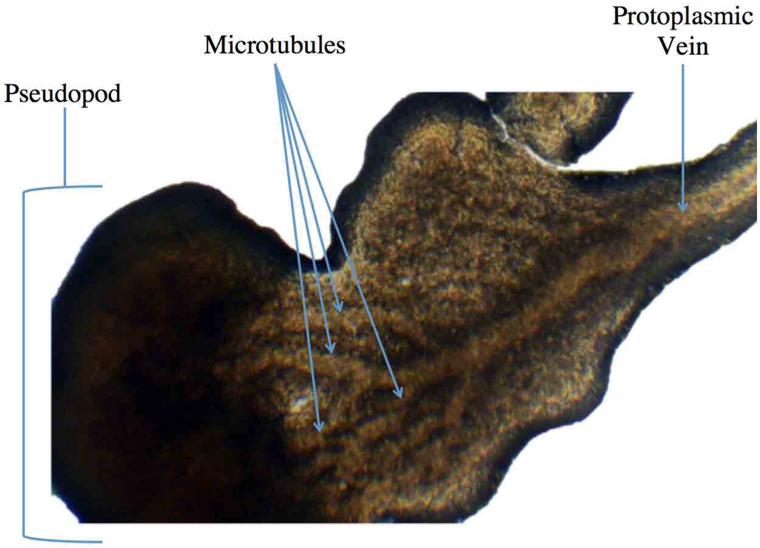

Figure 2.6: A microscope image of a pseudopod formed by cytoplasmic streaming pressure building in the anterior of the plasmodium.

(84). A plasmodium's contraction-relaxation rhythm is determined by both local stimuli and neighbouring oscillations (85). Areas of the cell that have a higher frequency take a phase lead and create waves of excitation that propagate towards areas of lower frequencies (86). The direction of shuttle streaming is dependent on the spatial difference of contraction-relaxation phases (87). When stimuli that attract the plasmodium come into contact, the local region's frequency increases. Conversely, upon repellent contact, the region's frequency decreases (80, 83, 85, 86). Some examples of observable taxes in plasmodia are negative phototaxis to blue light (88), positive chemotaxis to glucose and various carbohydrates (86), negative chemotaxis to salt and metal ions, and thermotaxis to temperatures that are favourable (89).

Biologists have been interested in the plasmodium's shuttle streaming for over half a century. Investigations into this phenomenon have aided researchers in understanding the mechanisms behind cytoplasmic streaming. Scientists have published numerous studies (e.g. (67, 68, 75, 76, 90, 91, 92, 93)) and, to this day, shuttle streaming in plasmodia of *P. polycephalum* continues to gain significant interest. One of the aspects that researchers find most intriguing is the controlling system behind the oscillatory actin-myosin contractions, which is still not fully understood. Indeed, several researchers have developed hypotheses in answer to Wohlfarth-Bottermann's (75) question *"what is the physiological nature and location of the oscillator and is there some sort of 'pacemaker' or 'trigger' which governs the contractions?"*. There is evidence that concentrations of intracellular chemicals change upon stimulation. For example, repellents increase ATP concentration (94) and attractants decrease pH (95). Calcium is known to play a role in the regulation of processes such as shuttle streaming (86) and phototaxis (96). Here, the fluctuation of free calcium in the cell is believed to be the physiological signal that initiates these processes (97). Plasmodia store calcium within mitochondria, endoplasmic reticula, and granules, which take up calcium ions.

A property of plasmodia is that they are electrically active. Such electrical behaviour is believed to be a result of ionic movement and fluctuation. Here, intracellular ions undergo locomotion with shuttle streaming. Ionic concentrations can fluctuate as a result of several different processes. For example, as intracellular stores (e.g. mitochondria) release and uptake ions or as ions are transported across a membrane barrier (e.g. through voltage-gated ion channels). The latter of these processes is known to play a role in muscle movements. Whiting et al. (98) have postulated that ion channels control actin-myosin contractions in *P. polycephalum.* Several researchers have also provided evidence that there is a relationship between a plasmodium's peristaltic activity and electrical membrane potential (99, 100). In an early study, Kashimoto (101) found that the rhythmic bioelectric system in the plasmodium oscillates at periods of $\approx$ 1.5 minutes with an amplitude of $\approx$ 5mV. Since, numerous researchers have investigated this phenomenon and it is now commonly accepted that plasmodia oscillate at periods of 50-200 seconds with amplitudes of 5-10mV (4) (Figure 2.7). Bioelectrical characteristics vary dependent on environmental conditions and the physiological state of the plasmodium (102). In a recent study, Adamatzky and Jones (4) examined the bioelectrical activity of a 'free range' plasmodium and discovered emergent patterns which uniquely characterise spatial dynamics and physiological state. Investigations into bioelectrical phenomena in the plasmodium have aided in understanding the mechanisms behind the oscillators that control actin-myosin contraction (103). However, currently we can not say for sure that bioelectrical and peristaltic activity are controlled by the same system, although this is the popular hypothesis.

It is important to acknowledge that there is still a lot to learn about this unicellular organism, which still continues to excite researchers (104).

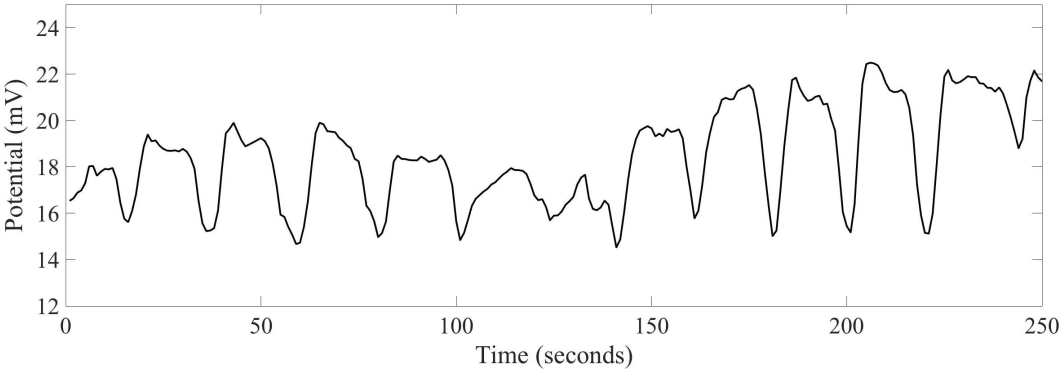

Figure 2.7: A time versus voltage plot depicting a typical example of the plasmodium's electrical membrane oscillations.

2.6 Physarum Machines

The term *'Physarum machines'* was coined by Adamatzky to develop a formal paradigm on computing with *P. polycephalum*. He explains that:

> *"A Physarum machine is a programmable amorphous biological computer experimentally implemented in plasmodium of Physarum polycephalum"*.

The genesis of UC with *P. polycephalum* came in the year 2000 when Toshiyuki Nakagaki, Hiroyasu Yamada, and Ágota Tóth, experimentally demonstrated that they could manipulate the behaviour of the plasmodium to approximate shortest paths (10). In these experiments, Nakagaki et al. inoculated samples of plasmodia within a labyrinth where they placed cut plastic film on agar to represent walls around moist pathways. This arrangement caused the plasmodia to coalesce and spread over the moist surface that formed the labyrinth's pathways. Then, the team placed oat flakes at the entrance and exit, causing the plasmodium to develop a single protoplasmic tube between the sources of food, revealing a pathway through the maze.

Since Nakagaki et al's experiment, research into computing with *P. polycephalum* has increased exponentially with laboratories worldwide developing experimental prototypes. Each of these prototypes harness one or several aspects of the organism's behaviour and physiology to create sensing, actuating, and computing systems, along with electronic circuits and components. One of the major contributors to Physarum

Machine research was the recently concluded European Research Council-funded PhyChip project[1] (105).

2.6.1 Approaches to Implementing Physarum Machines

In this section, we look at some of the methods researchers have used to implement Physarum Machines. Such an insight provides the reader with knowledge of the approaches that are adopted in research presented in the proceeding chapters. The quantity and diversity of existing prototypes make it difficult to present details on every individual approach. As such, I have split the devices into two broad categories —classical and contemporary —and explain some of the key methods developers have used to harness the organism's behaviour and physiology.

Classical Physarum Machines are designed to solve problems by taking advantage of the organism's ability to optimise its shape and react to its environment. Such prototypes adopt approaches that are derived from the early *P. polycephalum* UC experiments. Contemporary Physarum Machines encapsulate all other implementations that fall outside the first category. These devices take a myriad of different approaches to exploiting the organism's behaviour.

2.6.1.1 Classical Physarum Machines

Researchers have applied the plamodium's ability to create efficient protoplasmic network configurations to solve a range of problems. Adamatzky explains that there are two approaches here (106). The first is to inoculate the organism so it covers the majority of the computational space. Then, once it has spanned over the space completely, food is positioned to cause the plasmodium to forge an efficient distribution network between the sources of food. The second approach is to harness the organism's ability to react to chemical stimuli with natural parallelism (86). Here, the plasmodium is inoculated into the space and chemoattractants are configured as necessary. Initially, the organism will explore the space in a somewhat random fashion until it discovers a chemical gradient that surrounds a chemoattractant. At this point, it will cease foraging on other fronts and propagate along the gradient to the attractant. Chemorepellents can also be introduced into the environment to get the organism to avoid certain areas.

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[1] `http://www.phychip.eu/` (Accessed: 13 November 2016)

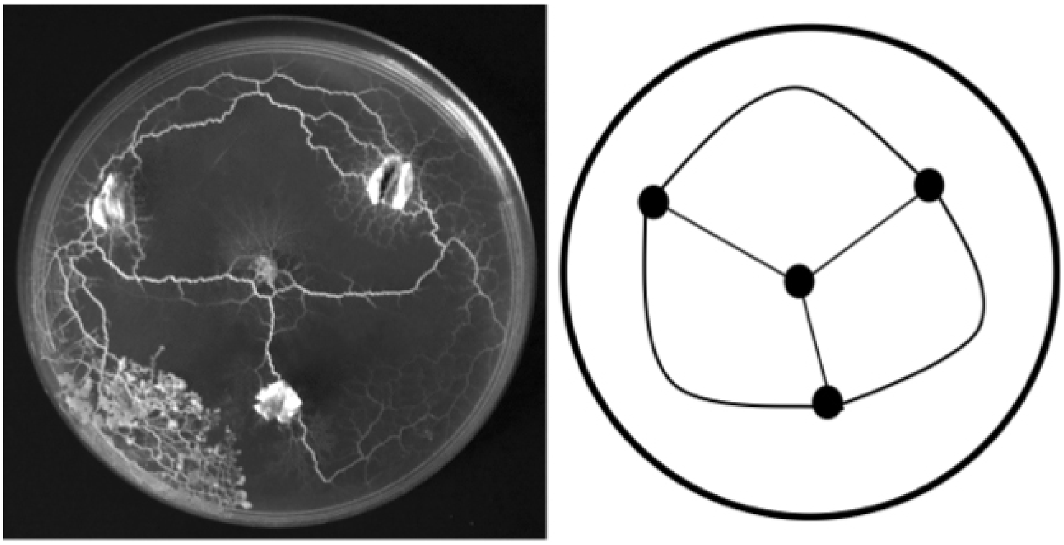

Figure 2.8: The visual result of a culture of plasmodium in relation to a planar graph. Shown are several areas of colonisation (nodes) connected via a network of protoplasmic tubes (edges).

In these approaches, the spatial distribution of nutrients and environmental conditions are a method of inputting data to the computation scheme. The program is coded by the configuration of attractant and repellent stimuli, and the result of a computation is the subsequent protoplasmic tube network (9), which takes the form of a planar graph where food sources represent nodes and protoplasmic tubes are edges (Figure 2.8). Developing Physarum Machines this way requires little in the way of equipment and consumables. All that you need is the organism, some food, and a way of monitoring progress (e.g. a camera). As plasmodia migrate slowly, it takes a significant amount of time (several days) for Classical Physarum Machines to produce results.

Some examples of Classical Physarum Machines are:

- Implementation of logic gate schemes (107, 108),
- Construction of Voronoi diagrams (109, 110),
- Route planning, shortest path, and route evaluation (78, 111, 112, 113, 114, 115),
- Developing proximity graphs (116),
- Constructing spanning trees (117),
- Evacuation pathways (118),
- Numerous others, see (9) for a selection of prototypes that harness this approach.

2.6.1.2 Contemporary Physarum Machines

As interest in UC with *P. polycephalum* has been increasing, so has the complexity of prototypes. Over the past 15 years, researchers have implemented and reported on an incrementally vibrant and diverse range of experimental Physarum Machines. Such prototypes do not necessarily look to build complete computing architectures; rather, some aim to develop sensors, actuators, or hybrid electrical systems. Furthermore, implementation methods, in many cases, are specific to application and have evolved as heightened research has increased our understanding of the organism's biology. To present such a diverse range of prototypes, this section first introduces some of the key behavioural and physiological aspects that have provided researchers with a basis for their experiments. Please note, that the presented aspects are selected due to their relevance to this research. Then, a table (2.1) lists some examples of the prototypes that investigators have implemented and their respective applications.

Those prototypes listed in the previous section all take advantage of the organism's spatial abilities. These systems require periodic visual inspection of the organism to interpret the computation's results, which normally requires human intervention. Contemporary Physarum Machines are often interfaced with a conventional computer, which is programmed to automate the interpretation of various behaviours. Moreover, researchers have looked to harness much quicker aspects of the plasmodium's behaviour and physiology in order to move towards real-time systems.

One feature that has been extensively exploited in Contemporary Physarum Machines is the organism's oscillatory behaviour. As previously discussed, *P. polycephalum* oscillates protoplasm around its network of protoplasmic tubes through the process of shuttle streaming. Under a microscope, this streaming activity is highly visible and active in real-time. Numerous studies have investigated how patterns in oscillatory behaviour relate to physiological states and environmental stimuli (Section 2.5.2). Such knowledge provides UC investigators with methods of interaction to provoke behaviour (for data input) in order to produce a measurable response (for results).

Oscillatory behaviour can be harnessed for UC in various different ways. One option is to optically monitor discrete areas of the plasmodium's morphology with cameras and non-invasive illumination. As peristaltic activity is related to membrane potential, another approach is to monitor the organism's electrical dynamics. The plasmodium exhibits a rich spectrum of extracellular electrical oscillations, which can be recorded with electrodes made out of bare wire and monitored on a computer via inexpensive analogue-to-digital converters (ADC) (4). Electrical oscillatory behaviour provides continuous data without the need for complex visual processing and specialist lighting. In regards to implementing UC systems, this phenomenon supplies developers with efficient means of automating the behaviour interpretation process.

The plasmodium's electrical properties have more recently been explored for developing bio-hybrid electronics. *P. polycephalum's* morphology during its plasmodium phase is conducive to implementing these types of systems due to its natural ability to implement networks of conductive pathways. Furthermore, the amorphous nature of the unicellular system and the way it migrates means that its form can be delineated to conform to an electrical schematic. Some of the possibilities researchers have explored by implementing bio-hybrid electrical systems with *P. polycephalum* are its ability to self-heal, form connections in difficult to access locations, and how biological processes affect conductance.

Table 2.1 contains a selection of Contemporary Physarum Machines. The reader is directed to (119) for a comprehensive overview of existing Contemporary Physarum Machines.

Function of Prototype	Harnessed Behaviour	Description
Colour Sensor (120)	Extracellular Membrane Potential	Adamatzky demonstrated that when plasmodia are stimulated with red and blue light they produce unique patterns of oscillatory surface potential.
Chemical sensor (98)	Extracellular Membrane Potential	Whiting et al. provided evidence that the plasmodium's oscillatory extracellular potential changes amplitude and frequency after exposure to volatile organic chemicals. Furthermore, they presented findings that such changes in potential were relative to specific exposures, allowing one to differentiate between chemicals.
Tactile Sensor (121, 122)	Extracellular Membrane Potential	Adamatzky implemented tactile sensors with plasmodium, which could react to the application and removal of a load. Such sensors functioned via an analysis of the organism's extracellular potential while being stimulated with capillary tubes.
Biological Wires (123)	Protoplasmic Tube	Adamatzky investigated the feasibility of using protoplasmic tubes as conductive pathways for novel computing devices. He demonstrated that the tubes remained functioning under voltages as high as 20V, could be insulated with silicon, can self-repair, and be routed with attractant and repellent stimuli.
Electronic oscillator (124)	Peristaltic Contractile Activity	Adamatzky showed that, due to peristaltic contractile activity, the resistance of a plasmodium's protoplasmic tube oscillates at an average period of 73-seconds and average amplitude of 0.6MOhm. He then went on to run experiments which showed that under a DC voltage, *P. polycephalum* could potentially be employed as a living electrical oscillator.
Learning Chip (125)	Electrotaxis	Whiting et al. ran experiments to demonstrate that the electrical conductivity of the plasmodium's protoplasmic network shows pathway-dependent plasticity. Here, the team grew the organism over an array of electrodes which transmitted electrical stimuli. Their results showed that the application of voltage between two electrodes increases connectivity of the protoplasmic network linking them while decreasing connectivity elsewhere.
Microfluidic Logical Gates (126)	Intracellular Shuttle Streaming	Adamatzky and Schubert discovered that tactile stimulation of the protoplasmic tube causes blockages and the redirection of the endoplasmic flow. Using this behaviour, they developed a logic gate framework where tactile stimulation represented input and the operation's results were represented by tracking where the organism redirected endoplasmic flow.
Robot Control (127)	Phototaxis	In this project, scientists developed a six-legged robot whose movement was controlled by interfacing with a bio-hybrid chip. This device used a circuit grown out of plasmodium which took the form of six circular wells that each represented an oscillator. These were arranged in a circle and were joined together at the centre through six channels. The robot was fitted light sensors that relayed intensity information to a computer, which instructed a projector to shine light on select areas of the biological circuit. With a camera, the computer then recorded the resulting phototaxis by measuring the thickness of intracellular oscillations, which the team subsequently used to naturally manoeuvre the robot away from light.

Table 2.1: A table containing an overview of selected Contemporary Physarum Machines.

2.7 Discussions

The computer has provided musicians with an unprecedented ability to advance musical possibilities. Such possibilities are intimately connected to developments both in computing software and hardware. For example, in the early CM experiments, computer-based sound synthesis was bounded to the sound generation mechanisms of the computing machines: variable sound was not possible until the DAC was introduced. Thus, future computing technologies are likely to provide new possibilities and pathways for music. However, it is commonly acknowledged that we will one day reach the development potential threshold of our current computing paradigm. Such a consensus has caused research into UC to increase over the past decade. UC is an emerging field of investigation that researches new approaches to implementing computing systems. Given the field's novel and innovative nature, we would expect computer musicians to show interest. However, as information in the next chapter will explain, there has been little in the way of cross-disciplinary investigation. It is likely that such a short fall is due to UC prototypes historically being an unrealistic option for non-experts.

The recent progress with *P. polycephalum* has increased the visibility of UC research. Moreover, it has created a climate where designing and implementing biological UC prototypes is feasible for engineers and computer scientists. In the majority of cases, such research does not require the use of a biological or engineering laboratory and can be recreated without strict safety requirements and ethical issues (104, 128). Culturing plasmodium for experimentation is also a low-maintenance task. The organism does not require special biological supplies, can be fed with normal food goods, and, once the experiments are over, can be put into hibernation mode (sclerotium) until next time. Such accessibility and ease of prototyping are likely to be the main contributing factors to the *"veritable explosion of research"*(129, p.3) —as put by one scientist —into prototyping with *P. polycephalum*. The exponential development of these genuine prototypes over the past 15 years is unprecedented in UC. As a result, there is now an extensive tool kit for the UC novice who is interested in experimenting with *P. polycephalum*. These attributes suggest that this biological substrate may be a candidate for UC outsiders to begin investigating and understanding whether this emerging area of science has real-world potential. In relation to investigating UC for

CM, *P. polycephalum* offers an opportunity to gain insight into how UC may provide new pathways for music and related technologies. Such an insight will provide answers to **RQ1**, **RQ2**, and **RQ3**.

P. polycephalum's user-friendly nature is exemplified by the emerging communities of practitioners holding events and establishing forums centred on sharing work and ideas. One example of such a community is 'The Slime Mould Collective'[1], which operates an online forum of over 700 members. Furthermore, with the advent of funded research projects that are dedicated to investigating UC with *P. polycephalum* (e.g. the Phychip project), there is an increasing quantity of academic workshops and conferences being held. Dissemination of work with the organism is also thriving. Over the years of this PhD research, progresses from investigations have been reported on by several mainstream media channels[2], some of which featured work from this thesis. Film-makers have even produced a documentary[3] that features an overview of the current investigations with the organism (130). Thus, the present climate is conducive to achieving a good outreach to the CM community about work with *P. polycephalum*.

By reviewing the nature of existing Physarum Machines, we can identify qualities that are inherent of implementing this type of technology. In some cases, such qualities are likely to be restrictive if not overcome when developing systems for the CM community. For example, the robustness of prototypes is not always a pressing concern when the system is developed in a laboratory and is not going to be moved. However, CM devices are often transported and subjected to testing environments; for example, positioned on a stage with hot lighting. Prototype lifespan is also often short, with some implementations causing damage to the organism that takes a significant amount of time to heal. In many cases, Physarum Machines take time to grow before they can be used, which can be tedious to the casual user who does not plan their creative practice in advance. These types of issues are highlighted and addressed throughout the thesis in order to answer questions **RQ2**, **RQ3**, and **RQ4**. It is important that the approaches to address issues do not negate *P. polycephalum's* accessibility and thus the rationale for experimenting with it for CM.

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[1] `http://slimoco.ning.com/` (Accessed: 13 November 2016)

[2] `http://www.scoop.it/t/musical-research` (Accessed: 13 November 2016)

[3] `http://www.creepinggarden.com/` (Accessed: 13 November 2016)

Using biological matter within technology also provides us with potential benefits. Some key advantages of harnessing living systems are their self-healing abilities, energy efficiency, and low impact on the environment. These systems also exhibit complexities that may be a useful feature when harnessed in creative technology. For example, although devices whose behaviour is not 100% predictable are likely to be detrimental to the vast majority of applications where our conventional machines excel, in the creative domain, variations can be desirable and even sought after: composers have been known to use a wide span of different and non-deterministic processes (e.g. stochastic) to evolve their compositions. Of course, degrees of predictable control are also important in creative applications, but, as explained previously, UC is not looking to directly replace our current systems. Rather, it is a pursuit to enrich and go beyond our current technology's remit. Thus, implementing musical systems on a biological substrate such as *P. polycephalum* may allow us to extend the functionality of our current technological offering in CM. Here, it may be possible to develop technology that works differently when stimulated with certain phenomena or naturally learns and adapts its architecture according to how it is used. Although it is possible for us to achieve some of these things with our conventional machines, they would require significant work to implement. For example, it can be time consuming and expensive to change our silicon computer's architectures, whereas biological systems alter their form naturally in accordance with environmental conditions.

2.8 Chapter Summary

This chapter has presented background information on a number of different areas related to this thesis. It first detailed the story behind the genesis of CM. The purpose here was to acknowledge how advances in Computer Science directly affected the field of CM and how it is likely that this trend will continue. From this point, the chapter moved on to discuss the future of computing technologies and introduced UC along with some of the reasons why there is heightened interest in the field. An analysis of the UC field suggested that computer musicians would find it difficult to access genuine UC prototypes due to their resource-intensive and complex nature. It was then established that *P. polycephalum* is a unique addition to the field of UC due to it being a low maintenance and user-friendly substrate.

Discussions on the information presented in this chapter highlighted that current interest in *P. polycephalum* positions us well to disseminate research into UC for CM. The findings from reviewing current Physarum Machines indicated that there were a number of issues that needed to be considered when harnessing *P. polycephalum* for CM. It was also stated that when addressing such problems it is crucial that accessibility to computer musicians is of the utmost importance. The discussions went on to talk about some of the potential benefits of harnessing living systems within technology and how these may provide new pathways for music and related technologies.

In summary, from the information presented in this chapter some key areas for further research are:

- Accessibility of prototype to the computer music community,
- Feasibility of use outside the laboratory,
- Enriching our current technology in CM with aspects of UC,
- Adopting appropriate methods of overcoming limitations that are inherent of harnessing biological systems in technology.

3

Previous Work on Unconventional Computing in Music

3.1 Chapter Overview

This chapter introduces the emerging field of UC for CM. It presents the diverse selection of projects that are establishing the field by exploiting the behaviour of genuine and utopian UC systems for CM. The aim of the chapter is to give the reader an insight into the approaches that other practitioners have used to harness aspects of UC for sound and music. Such an insight also provides further justification for the motives behind investigating *P. polycephalum* for CM.

Nearing the end, the text pays particular attention to the previous CM work with *P. polycephalum*. Here, an initial investigation that used the organism for sound synthesis is presented. This work provided the foundations for the initial experiments that are presented in the forthcoming chapter.

The structure of this chapter is as follows:

- 3.2 - Introduction
- 3.3 - Unconventional Computing in Music with Computer Modelling
- 3.4 - Investigations into Genuine Unconventional Computing for Music
- 3.5 - Discussions
- 3.6 - Chapter Summary

3.2 Introduction

In CM, there is a tradition of experimenting with emerging technologies (28, 131), which stems from the field's genesis (as exemplified in Section 2.3). Until recent years, however, computer musicians have left developments put forward by the field of UC largely unexploited, which is likely due to the field's heavy theoretical nature and lack of accessible prototypes. As Adamatzky writes: *"unconventional computing is chock full of theoretical stuff. There are just a handful of experimental laboratory prototypes. They are outstanding but difficult for non-experts to play with."* (9, p.v). This is particularly the case in regards to genuine UC prototypes, where non-experts face constrains such as acquiring advanced laboratory equipment and specially trained personnel. Furthermore, the sheer cost of some genuine UC prototypes are unrealistic for most CM research groups and individual creative practitioners. For example, commercial quantum computer manufacturer D-Wave[1] sell their machines under a price tag of around $15 million (132). Accessibility constraints are likely the reason why the majority of existing work in CM that investigate areas commonly addressed in UC use computational modelling. It was not until more recent years where CM researchers have begun experimenting with genuine UC prototypes. Therefore, the previous work presented in this chapter is split into two sections, those that used computer models and those that used genuine UC substrates.

Existing applications of UC in CM appear to focus mainly on sound synthesis or algorithmic composition, which is similar to those approaches adopted in the early CM experiments (Section 2.3). In sound synthesis implementations, aspects of the UC system's behaviour is converted into sound via a sonification model. Sonification, as defined by Kramer et al., *'is the use of nonspeech audio to convey information"* (133). For these applications, some form of behavioural information is gathered from the UC system and used either to create sound directly (e.g. where datum may represent one audio sample) or modify the parameters of a sound synthesis scheme (e.g. where data is mapped to control parameters such as pitch or amplitude). Investigators who have adopted sonification techniques with UC tend to be in pursuit of either developing a better understanding of the substrate's behaviour, or engineering novel instruments

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[1] `http://www.dwavesys.com/` (Accessed: 13 November 2016)

and interfaces. In the case of algorithmic composition, aspects of the UC system's behaviour are formalised into an algorithm that processes information in some capacity to produce results that can be applied in musical composition. For instance, an algorithmic application could produce the arrangement of musical sections or generate actual notation. This approach encapsulates the recently formulated concept of musification, where data is mapped into musical structures (134). It is important to note that mapping algorithms are also a key part of the sound synthesis implementations. The term algorithmic composition is used in this text to refer to using formalised procedures to generate or arrange musical structures (e.g. notes and durations).

Before discussing existing projects, it is necessary to note a few things. Firstly, as there is no defined standard for classifying UC systems, this survey only includes work that is either explicitly investigating UC for CM or musical studies harnessing technologies that are frequently explored in UC. Furthermore, research was only included if it was well documented in academic literature. Secondly, due to the broad nature of UC, its associated accessibility constraints, and the embryonic nature of studies into UC for CM, current examples are not necessarily related in terms of progression. The musical experiments are not always looking to build upon findings from previous investigations. As such, the forthcoming review presents projects that are establishing a field, not building upon existing ideas. Indeed, there are no formalised methods, accepted best practises, or established applications of harnessing UC for CM: as is commonly expressed in UC research, it *"all depends on our interpretation and imagination. Just our fantasy holds"*. (49, p.100). Thirdly, there is not much diversity in regards to the research groups studying UC for CM, and work is scarcely repeated by other members of the CM community; this is particularly the case where researchers have harnessed genuine UC systems.

The diverse selection of UC systems employed for CM can make it difficult to analyse existing work to build applicable knowledge to apply to the research contained in this thesis. For example, specific technical issues related to harnessing a quantum computer for music are likely to be fundamentally different to those that arise when harnessing a Physarum Machine. Therefore, it is important for me to delineate the criteria used for comparison and evaluating success within this chapter. The survey does not focus on the specifics of any low-level technical issues. Rather, it looks at more high-level aspects that are in keeping with the nature of this research's questions and aims. For example, why and how is the system being used for CM and is it fit for such a purpose? Here, classifying something as fit for purpose depends on the investigators motivations. If one is presenting an instrument for use in musical composition, does it conform to basic criteria that make its application feasible? Thus, discussions are centred firstly on the approach to harnessing the UC system for music and what the investigator was attempting to achieve. Here, the motives behind each implementation are reviewed to ascertain whether they were in pursuit of developing new CM tools, a single unique musical artefact, or scientific exploration through sound (e.g. sonification). It is difficult to evaluate the results of these projects in terms of music as this is a matter of personal preference. Thus, where possible, the musical results of these studies are evaluated in accordance with the researcher's motives. Each project's accessibility to the CM community will also be addressed to ascertain any constraints that are limiting the dissemination of progresses.

3.3 Unconventional Computing in Music with Computer Modelling

The notion of harnessing natural living systems for musical inspiration is not new. Computer musicians have explored using models of real-world phenomena since the 1980s. In fact, formalising compositional processes by establishing and implementing algorithms is a long-standing method of composing music. It would be easy to assume that algorithmic composition resulted from the increasing ubiquity of computers. However, as cited in the majority of algorithmic composition publications, these methods of music generation can be dated back as far as the ancient Greeks, where the Pythagoreans believed that mathematics and music were unified fields (135).

Computers have, however, widened the scope of algorithmic composition and provided composers with the tools to implement these processes in real-time and in live performance (28). The universal nature of today's computer has allowed practitioners to adopt algorithms purposed for problems outside of the creative domain for music generation. For instance, algorithms designed to model biological, chemical, or physical systems. The notion of composing with computer models of natural systems is likely to be instinctive for many composers. As Brooks and Ross write *"Nature has been, and continues to be, a major source of inspiration for composers"* (136, p.27). Practitioners who adopted modelling approaches that today we consider to fall under the umbrella of UC often did so as a result of drawing relationships between an aspect of music and natural systems. An area of computational modelling that has been investigated by the CM and UC communities is Cellular Automata (CA) (50), which is discussed in the proceeding section.

3.3.1 Cellular Automata

Developed by von Neumann and Stanislaw Ulam as part of an investigation into the possibility of machine reproduction, CAs are computer tools that users can program to model the evolution of a system over time (50, 137). Such tools are discrete dynamical systems and can simulate aspects of biological and physical media that computer scientists have explored for UC; examples include, chemical reaction-diffusion, self-organisation, and natural spatially extended systems.

Conventionally, a CA is implemented on a computer as a grid of cells. Every cell can exist in a defined quantity of states, which are normally represented as an integer and displayed on the computer screen by colours. To enable the model to evolve, rules are applied to the cells informing them to change state according to the state of their neighbourhood. Typically these rules remain the same throughout the model, but this is not always the case. At time $t = 0$, each cell is assigned its starting state, which can consist of an inactive state and any number of active states. The model can then apply the transformation rules to produce a new generation ($t = 1$) of the grid. This process can continue for an infinite amount of iterations. Thus, *"cellular automata are mathematical models for complex natural systems containing large numbers of simple identical components with local interactions"* (138, p.1).

CA has been employed by a number of composers for both sound synthesis and algorithmic composition. The first composer to employ these tools for music was Xenakis in the 1980s, who is also widely considered the first composer to harness computer-based models of natural phenomena for music (139). Throughout his career, Xenakis was well known for his interest in nature stating that his musical works were *"repeating on a lower level what nature carries out on a grand scale"*(140, p.112). Xenakis's first piece composed with a CA was *Horos* in 1986, which premiered in Japan (139). In this piece, the CA was programmed to create chaotic evolutions using rules that were capable of simulating diffusion processes (141). It was these capabilities that motivated Xenakis to harness CA for music:

> *"They are very simple rules which can create structures on very large surfaces. It's related to the nature of fluids, for instance. For me the sound is a kind of fluid in time - that's what gave me the idea to transfer one area to the other. I was also attracted by the simplicity of it: it is a repetitious dynamical procedure which can create a very wealthy output."* (140, p.200)

Xenakis's notion that CA's dynamical nature is useful for music is apparent throughout investigations into harnessing CA for music. This is likely because space, time, and cell state are discrete in CA systems. Thus, as music and sound are time-based and can be considered to consist of a finite group of discrete values (e.g. notes, amplitudes, and durations), CAs are arguably well suited to be applied to the task of generating music/sound. In the case of *Horos*, Xenakis was particularly interested in how CA could be applied to orchestration to create unique timbres (139). For this piece, the CA grid was one dimensional and consisted of 23 cells that each represented a predetermined musical note. The cells could exist in any state from 0-4, with 0 being inactive. Active states 1, 2, and 4 corresponded to a specific group of instruments in the orchestra: brass, woodwind, and strings, respectively. Active state 3 was not assigned to any musical group. For each grid iteration, the configuration of cell states would determine which of the 23 notes would play and their distribution amongst the orchestral instrument groups. Thus the CA was harnessed to combine scales of predetermined durations and pitches to create an evolution of orchestral clusters over time (141). Xenakis implemented the mapping of CA cells to musical notes by hand. As the CA used to compose *Horos* simulated diffusion processes, the musical result is a lateral symmetry in the distribution of the 23 predefined notes around the centre pitch.

Following the release of Xenakis's *Horos*, other composers experimented with harnessing CA for generating sound and music, for example Bowcott (142), Bayls (143), and Millen (144), to cite but three. The rest of this section, however, focuses on two approaches to harnessing CA for CM that were developed into general-purpose CM tools and made freely available to the musical community. The rationale for focusing on these two systems is because they are considered to be successful case-studies that focused on providing creative practitioners with the ability to experiment with CA for music. Moreover, they demonstrate both the sound synthesis and algorithmic composition approaches.

Perhaps the most pioneering CA investigation in regards to creating reusable musical tools is Miranda's *Chaosynth* program (145), which he developed in 1992. This system was developed to exploit the self-organisation abilities of CA for granular synthesis. Miranda drew a comparison between the complexity of CA, where smaller interacting units together create emerging behaviour, and granular synthesis, where small sound grains create larger sound objects. The name Chaosynth is a contraction of two abbreviations: ChaOs, which is short for chemical oscillator, and synth, which is short for synthesiser. Thus, Chaosynth harnesses a CA model of reaction-diffusions to control the parameters of a granular synthesiser. Specifically, the CA models neural reverberatory circuits, which, put crudely, can be thought of as an array of oscillating nerve cells. The mapping approach developed by Miranda divides the CA grid into a number

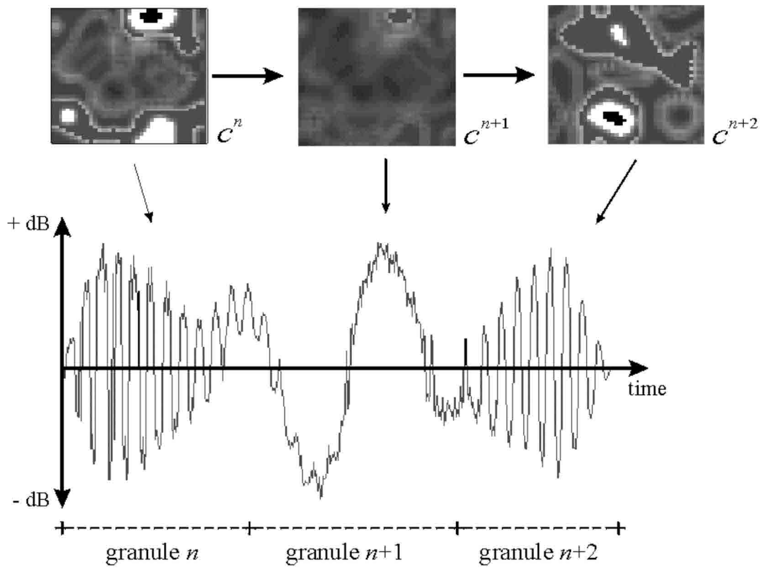

Figure 3.1: As the cellular automaton evolves at each time-step, Miranda's Chaosynth generates parameters to synthesise a sound grain. Picture taken from (3, p.352) with permission from the author.

of sections, which are each assigned to a sinewave oscillator. The user can specify the CA grid's dimensions, the quantity of oscillators, the allocation of cells to oscillators, and certain parameters of the model (e.g. the number of states, the initial states of the cells, and the quantity of grid iterations). Upon the automaton's grid refreshing, the system calculates the mean average state of each oscillator's area and maps the value to control the frequency of the respective oscillator, which then generates a sound partial of a user-defined duration and amplitude. All partials are subsequently combined to create a short burst of sound, lasting for a few milliseconds, referred to as a sound granule. Hence the synthesis technique: granular synthesis, where a rapid succession of sound granules produces a continuous sound. Each of these granules represents the entire automaton's grid at the respective refresh point (Figure 3.1).

The sonic results of Miranda's Chaosynth program are not ones that can be found in the real acoustic world. This is often the case with sounds that have been generated using granular synthesis techniques. By applying the organised behaviour of the CA model, however, the output of Chaosynth often sounds, as Miranda puts it, *"natural and pleasing"* (3, p.9). Thus, the application of the CA model for sound synthesis provides two major benefits. Firstly, it provides means of generating a massive amount of control data for the granular synthesis algorithm, which would be tedious to define manually. Secondly, the model's emergent behaviour creates organised spectral evolutions over time. The latter benefit is significant as many algorithmic approaches to produce control data adopt stochastic processes (146), which can produce dense, uneven, and uncontrollable results. Due to his success here, Miranda has gone on to produce a taxonomy of the different sound classes that Chaosynth is capable of generating (147). Such classes were based on the spectral evolution of sounds produced by the system. Miranda used this system to generate sounds for a number of pieces of electroacoustic music, including *Olivine Trees*, composed in 1993, which is believed to be the first piece of music to be composed on a parallel computer (148, p.250) (149).

Miranda has also developed a musical engine for generating notation using CA (150). In his system CAMUS, which stands for CA MUSic, he developed a method of mapping CA cells to musical notes using a Cartesian model. This program harnessed a popular CA model called Game of Life (GoL) (151) where cells can only assume one of two states: alive or dead. The model was originally developed by John Conway as part of a pursuit to find CA rules supporting patterns with slowest possible growth (152). For each grid iteration, CAMUS plays through every active cell, column by column, from top to bottom. Each of these cells defines two interval values from a given fundamental tone where the y coordinate represents the first interval and the x is the second interval. The fundamental note is chosen randomly from a set specified by the user before-hand. Once the musical engine has determined the three notes, it uses the states of each cell's neighbourhood to select a temporal template from a predetermined set. Miranda considers the output of CAMUS to be less successful than that of Chaosynth (153). Nonetheless, he has used the composition tool in several pieces: for example, the second movement of *'Wee Batucada Scotica'* for string quartet and *'Entre o Absurdo e o Mistéri'* for chamber orchestra. From his experiments with Chaosynth and CAMUS, and subsequently harnessing CA for algorithmic composition and sound synthesis, Miranda has expressed that *"cellular automata are more suitable for sound synthesis than for musical composition"* (154, p.191). The reason for this is likely due to musical composition involving aspects of culture and convention (e.g. musical keys), whereas sound synthesis lends itself to the complexity of CA.

3.3.2 Discussions on CA

The early pioneers that harnessed CA for music did so because they related the time-based nature of both CA and music. One of the key characteristics that render CA suitable for musical application is the discrete nature of their behaviour and functionality. These features make it fairly easy to map the CA model to parameters that will exemplify emergent behaviour in the sound/music domain. Furthermore, interacting with CA to create different outputs does not require extensive background knowledge. For example, as CA are complex systems, few parameter specifications can cause complex evolutions. Thus, CA modelling is an inviting way for computer musicians to experiment with aspects of UC (e.g. reaction-diffusion and self-organisation). There are, however, limitations. For instance, real-time use can be problematic due to the time the grid takes to regenerate. Furthermore, if the artist is interested in exploring the vast behaviour space of CA tools by implementing their own models, they need to be prepared to investigate the technical and theoretical background of both the phenomena they are looking to model and CA.

3.4 Investigations into Genuine Unconventional Computing for Music

In 2008-2009, the ICCMR at Plymouth University began an official investigation into UC for CM. Such an endeavour was pioneered by Professor Eduardo Miranda, whose research interests primarily focused on the use of the computer as a creative tool in the composition of sound and music (28). ICCMR has an extensive history of experimenting with CA for sound and music (See (155, 156, 157, 158) for examples), which is likely where their interest in UC stemmed from. On the ICCMR webpage, Miranda explains his rationale for investigating emerging computing paradigms for music:

> *"An important emerging development in computing research is the increasing tightening of the coupling between silicon machines and biological ones. Future computing technology will increasingly interface directly with our bodies (e.g., with the nervous system) and media other than silicon media will be increasingly harnessed to act as computers (e.g., bacteria-based).*" (159)

Due to most UC prototypes being difficult to access, the ICCMR established collaborations with research groups that were developing prototypes. The first of these was with University of the West of England (UWE) where Miranda et al. (160) ran an investigation into the feasibility of employing a hybrid wetware-silicon device with in vitro neuronal networks for sound synthesis. Research into UC with in vitro neuronal networks looks to study and harness the way neurons encode and process information, which is normally observed through complex electrical spiking interactions. Currently, there is a growing amount of interest in these devices with scientists having already developed methods of both culturing and interfacing with brain cells in vitro using a Petri dish furnished with a multi-electrode array (MEA). When cultured in vitro, brain cells have a tendency to form synapses —the structure that allows neurons to send and receive chemical or electrical signals. Once inoculated, the culture takes a few hours to start growing and a few days to establish an active living neuronal network (161). Using these techniques, the neuronal network's intricate bio-electrical dynamics can be studied and stimulated with impulses. Some examples of work that harnesses in vitro neuronal networks include DeMarse et al.'s implementation of a neurally controlled virtual animal (Animat) (162) and Potter et al.'s use of spiking patterns to control a robot's movements (163).

In the ICCMR's project, the investigators were interested in harnessing the spiking interactions between neurones to produce sound, with the main aim of creating a sound synthesis tool/instrument with a good level of control and repeatability. Here, researchers at UWE acquired brain cells from a seven-day-old Hen embryo and cultured them in vitro. Once grown, they positioned the culture into the MEA in such a way that at least two electrodes (one for input and one for output) made a connection into the neuronal network. The input electrode then stimulated the network with electrical impulses while the output monitored and recorded the subsequent spiking behaviour.

With the recording, Miranda experimented with a number of sonification methods using additive and granular synthesis techniques to convey the neuronal network's behaviour. In one example, nine oscillators made up the additive synthesis framework, with the first having its amplitude and frequency controlled directly by the recorded behaviour and the other eight being multiples of this value. Initially, the sound synthesis framework used the behavioural data in its raw, uncompressed form, which produced excessively long sounds. As such, they implemented a data compression algorithm that removed uneventful data. To achieve control over the wetware instrument, the authors considered a machine-learning algorithm aimed at controlling the spiking behaviour of the network. Currently, this part of the project is still in its infancy, but their initial results have shown that they can control spiking behaviour in about one-third of cases.

Building on the success of his project, Miranda went on to develop the idea further by moving past sonifying offline data. Collaborating with scientists at the University of Reading, Miranda devised a Musical Instrument Digital Interface (MIDI) controlled sound synthesiser where the instrument's timbre is defined by the electrical behaviour of a stimulated network of in vitro neurones (164). Here, the user plays a MIDI note which defines the synthesised sound's fundamental frequency. The instrument produces the sound's partials with 16 oscillators that are paired with 16 channels of the MEA. Each oscillator's frequency is obtained by multiplying the respective channel's electrical potential reading by the sound's fundamental. Commenting on the results of their investigation, Miranda et al. stated that there are many challenges that need to be addressed to progress with the work (164). The ability to produce different sounds with a degree of predictable control is an important property of a musical instrument. As the behaviour of in vitro neurones is still not completely understood, at this stage of knowledge predictable control is difficult to achieve. Therefore, the CM system is bound to advances in our knowledge of in vitro neurones: a field that is complex and may be difficult for a non-scientist to make breakthroughs in. The team suggested a future avenue of exploration where they build a sound-orientated understanding of such behaviour and investigate how they may use sound to stimulate and steer behaviour.

Another example of the ICCMR's work in this area is Kirke et al.'s (165) quantum computing system, *Q-Muse*. Quantum computing (QC) is perhaps the most high-profile UC idea discussed so far. QC takes advantage of quantum mechanics to perform computations; e.g., quantum superposition, entanglement, and tunnelling (166). Conventional computing machines process information serially. We can speed up these machines by speeding up the processors or by adding parallel processors. However, by harnessing the ideas of quantum mechanics, in theory we can speed up computation significantly. For instance, quantum superposition involves elementary particles, or *qubits* (the QC equivalent of bits), being in multiple physical states, e.g. being in multiple locations or representing multiple binary states simultaneously. This superposition ability allows for massive parallelism, which increases exponentially with the size of the system and is a key element behind the promised speed-up of quantum over classical computing (167).

To develop *Q-Muse*, Kirke from the ICCMR collaborated with research labs at the University of Bristol and Imperial College London to gain technical assistance and cloud access to a photonic QC at Bristol. The team developed the system for a musical performance called *The Entangled Orchestra*, which consisted of two movements for orchestra each harnessing different parts of the *Q-Muse* system. In the first movement the orchestra was divided in two sections, each with their own conductor. During the performance one of the conductors had the ability to entangle the orchestra by pressing a button. Upon doing so, the *Q-Muse* system told the QC to enter a state of entanglement, the results of which controlled each of the orchestra's respective tempos in real-time. For the second movement Kirke pre-composed a score for the orchestra to play and, during the performance, sent parameter data to the *Q-Muse* system using gesture and button controllers. The system then sent such information to the QC in real-time, informing it to change parameters associated with superposition.

The subsequent effects of these parameter changes were measured and sonifyed using sine wave oscillators. Essentially, in this movement, the *Q-Muse* system was a musical instrument.

Kirke has gone on to establish a collaboration with the University of Southern California who has acquired a D-Wave QC. Currently, D-Wave is the only commercial QC manufacturer in the world, and only a handful of organisations have purchased their machines. D-Wave's approach to computing does not attempt to implement Boolean logic gates as our conventional computers do, and that of Bristol's photonic QC. Rather, it uses an Ising model (168): a kind of connectionist computing approach using graphs of interconnected networks of qubits. The D-Wave attempts to group qubits according to their spin values —a parameter that defines the state of a qubit —to find the lowest total energy configuration. Kirke has developed a harmony system that exemplifies the D-Wave's approach to computation through music. Here, the computer is programmed to generate arrangement options for a set of notes in the key of C Major, which harmonises with a user-provided input note (169). *qHarmony* is designed to take advantage of a QC's non-deterministic nature and ability to return multiple results. The system maps notes to spin values in such a way as to ensure collections of qubits representing notes with lower interval distributions contribute to a higher total energy than those representing notes with higher interval distributions. Thus, the D-Wave system attempts to select a collection of notes that together create a chord that does not contain note clusters. Kirke has presented the results and musical artefacts of his *qHarmony* system at the 2016 *Port Eliot Festival*, Cornwall, UK.

3.4.1 The Unconventional Computing for Computer Music Community

In 2013, the first Artificial Intelligence and the Simulation of Behaviour (AISB) Symposium on Music and Unconventional Computing[1] was held, which, to the best of available knowledge, was the first gathering of academics to discuss ways in which UC may be used for music. This symposium was organised by the ICCMR at Plymouth University and the ICUC at UWE, and had its proceedings published in a special issue of the International Journal of Unconventional Computing (170). Work presented at

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[1] `http://cmr.soc.plymouth.ac.uk/aisb13-music/` (Accessed: 13 November 2016)

this conference included further investigations into CA for sound synthesis (171), exploring morphogenetic self-assembly processes to analyse musical objects (172), and an approach to generate music using memristors (173). The latter of these projects is most relevant to the research presented in this thesis.

The memristor is a circuit element that has long been theoretically established but has only recently been realised in a physical form (see Section 5.3 for a comprehensive introduction to the memristor). Scientists have developed a keen interest in the memristor due to its behaviour being analogous to the way neurones communicate: memristors respond to changes in input by spiking in a similar way to synapses, which is giving rise to perspectives of developing 'brain-like' computers (174). Such spiking behaviour is understood to be a result of a change in voltage across a memristor's terminals. Thus, when any one memristor within a network is subjected to a sudden change in voltage, it causes a spike in current. Each spike creates a change in resistance across the next memristor in the network, which causes a change in voltage that in turn produces another current spike. Spiking can propagate around a network indefinitely under a constant voltage. Gale et al. explored using this spiking phenomenon as a method of music generation that went beyond the use of Markov chains (173). Here, the team simulated a memristor network for notes over two octaves that is reflective of a completed k-graph where nodes are notes, and each vertex is a memristor. Thus, every possible note transition is represented by a memristor. To begin with, they seeded each memristor's conductivity with values from a transition analysis of some pre-composed material. Then, a constant DC voltage is applied to the network. As a spike occurs, it is recorded via an ammeter and the respective memristor's note transition is triggered in the output. A separate network was built to generate tempo. The likelihood of a transition occurring is related to the connectivity of each memristor. As the network generates music, it alters the conductivity of the memristors, which subsequently evolves the style of the music created by the network.

3.4.2 Previous Work in Harnessing *Physarum polycephalum* for Computer Music

Before my time at the ICCMR, Miranda teamed up with researchers at UWE to investigate the possibility of developing a bionic instrument with *P. polycephalum* (175). In a parallel approach to the aforementioned sound synthesis with in vitro neuronal networks (160), Miranda et al. were not interested in directly studying the computational properties of the organism. Rather, they were interested in whether the behavioural aspects that rendered *P. polycephalum* interesting for computation, were indeed interesting and usable for music/sound.

In this collaboration, researchers at UWE collected electrical behavioural information every second from a culture of plasmodium using techniques they had developed in a previous study (4). Here, the team recorded the plasmodium's electrical extracellular oscillations across eight isolated agar-coated bare wire electrodes, which they arranged in a linear fashion across the middle of a 9cm Petri dish. On top of each electrode, they placed an attractant (oat flake) to entice the organism and facilitate colonisation. After the collection process, which took several days, the recorded data was compressed to filter out uneventful entries.

Harnessing the results provided by the researchers at UWE, Miranda developed a sound synthesis framework to sonify the behaviour. Here, he scaled the data set and mapped it to control the parameters of a set of oscillators. Each oscillator represented an electrode's data set where the entries were mapped to control their amplitude and frequency parameters. For each datum within the set, the oscillators produced a 30 millisecond sound partial, which represented each electrode's potential at that point. Subsequent partials were then sequenced together to form a larger sound event lasting a few minutes. To ascertain whether his approach to translating electrical readings into sound were effective, Miranda compared a cochleogram of rendered audio against line plots of the organism's extracellular potential. The comparison denoted a strong morphological relationship (160).

Although the results of this project were sonically interesting and could be used by musicians in several different ways, the time needed to collect the data is tedious and renders the instrument unusable in a live situation. As a result, the team addressed the problem by experimenting with a computer approximation of the organism (176), which allowed for a real-time implementation of their synthesis instrument. This simulation, called *Pixiedust*, is a multi-agent system that models the migration behaviour of the plasmodium. The model is programmed so low-level interactions between agents create emergent transport networks around attracting and repelling sources. As *Pixiedust* does not model electrical oscillatory behaviour, the team recorded the agent population size at virtual electrode sites within the model (experiments have demonstrated that there are correlations between this value and real electrical behaviour (4)). By replacing the live organism with a model, the team's sound synthesis algorithm can be seeded with data much quicker. Moreover, the simulation allows the user to add/remove attractants and repellents in real-time, thus providing a more expressive interface for the instrument to be played.

Miranda furthered his musical work with *P. polycephalum* in the piece *Die Lebensfreude*, which was composed for an ensemble of five acoustic instruments and six electroacoustic tracks. *Die Lebensfreude* explores harnessing *P. polycephalum* for both sound synthesis and algorithmic composition. For this piece, Miranda continued to collaborate with researchers at UWE in order to maintain access to the *Pixiedust* model. This simulation generated all the data for *Die Lebensfreude*. For the six electroacoustic tracks, the model was set up to simulate the previous experiments where electrodes were arranged linearly and the data fed into the pre-developed sound synthesis framework. The scores for the acoustic instruments were generated by creating a foraging simulation that consisted of eight virtual electrodes. As the simulation ran, readings were taken from the electrodes sequentially. Every electrode was associated with a set of musical events, which were all assigned to thresholds of activity. Therefore, the magnitude of each electrode's reading determined which musical events featured in the output. This simulation was replicated to generate material for each of the six acoustic instruments.

3.5 Discussions

UC for music is still very much in its infancy, with limited explorations using genuine UC prototypes. Each of the explorations described in the previous sections resulted in fairly basic outcomes in terms of music and sound. However, we should not worry at this stage of development that the UC schemes and their results are fairly primitive when compared against the capability of our desktop machines. After all, today's computing approaches have undergone 80 years of development. Furthermore, CM on these machines has been around for 70 years, which gives our conventional paradigm a significant lead in regards to development. If we compared the results of the early computer music experiments against the computer-generated music of today, they would too seem primitive. Furthermore, it should not be a problem that experiments in UC for music are taking a heavily exploratory approach: exploiting the computing media's behaviour and architecture not just strictly their computational properties. Scientists took similar approaches when experimenting with the musical abilities of the CSIR Mk1 and Ferranti Mark 1 computing machines.

Although we appear to be taking a historically similar approach to begin our musical journey with UC, we should still look to learn from the past to ensure we best position ourselves for success. One of the key problems that prevented exponential momentum from building in the early years of CM was accessibility: computers were expensive, huge, and not many people understood how to use them. As I stated previously, such constraints are already prominent in UC. For example, presently in vitro neuronal networks and quantum computers are likely to be out of reach for the average computer musician. It is also worth noting that each of the discussed uses of UC for music were developed in collaboration between CM research departments and various science departments. These collaborations further highlight the accessibility constraint. Although such working partnerships are fitting for the interdisciplinary nature of UC for CM, they can also be limiting from the perspective of the computer musician. For example, the musician is reliant on someone else's time, facilities, and possible conservatism. Furthermore, it is unfeasible to believe that the average musician has the necessary contacts to secure the required collaboration. It is also significant to establish how important the ability to simply 'tinker' with technology is in creative disciplines.

Miranda states that musicians *"perhaps more than any other class of artists, have always been acutely aware of the scientific developments of their time...and have always looked to science to provide new and challenging ways to study and compose music* (28, p.xv). Thus, to build momentum in the study of UC for CM, accessibility is of high importance. The frontiers of the investigations must not only be concerned with breaking new ground, they should also seek to entice and encourage computer musicians who are interested but hesitant to explore the potential of UC paradigms in their works due to the difficulty of finding schemes to adapt to their needs.

By investigating the opportunities and challenges related to harnessing *P. polycephalum* for CM, this research looks to begin a journey into how technology implemented on different substrates may provide new pathways for music. Before this investigation, as the presented survey shows, there were only a handful of studies where researchers harnessed genuine UC systems for music and sound synthesis. These projects, presented above, are excellent, but the vast majority were solitary explorations that had a high novelty factor but were difficult for the computer music community to adopt and develop. Therefore, they offer little knowledge of how these emerging computing substrates may be useful in CM.

This research deploys *P. polycephalum* in a range of different CM areas. Such a process was designed to develop an appreciation of the type of applications where aspects of UC may provide means of enriching or going beyond our current CM technology. Due to the journey approach, this thesis is not exclusive to one area of CM. Thus, the previous and current chapter covered much ground to inform the reader on the necessary areas.

3.6 Chapter Summary

This chapter has delivered a survey of existing investigations into UC for CM. Findings from research surveyed in this chapter exemplify the problem of accessibility for practitioners who want to harness genuine UC systems. Here, the majority of explorations were found to be collaborative efforts between musicians and scientists/engineers. This arrangement means that the musician is reliant on someone else's time, facilities, and possible conservatism. Although collaborative projects are often highly productive, because of the accessibility constraints of UC prototypes, computer musicians are likely to find it difficult to build on any published work. Thus, it was highlighted that if we are to build momentum and the dissemination of UC for CM, then accessibility is of high importance. The chapter then went on to introduce and suggest that the biological computing substrate *P. polycephalum* may be a good candidate for research into UC for CM.

4

Preliminaries and Initial Experiments with *Physarum polycephalum*

4.1 Chapter Overview

This chapter presents the initial steps of this research journey. Firstly, the text details the experimental preliminaries: *P. polycephalum* sample acquisition, culturing and farming, safety considerations, measurement equipment, and methods of interaction. The chapter also provides information on the biological suppliers that have provided the necessary consumables and tools for carrying out this research.

The second half of the chapter presents initial experiments into harnessing the organism for CM. Such experiments are aimed at developing a practical and CM-oriented understanding of *P. polycephalum's* behaviour and physiology (Waypoint 1). In line with the metaphor of a research journey (Section 1.4), these experiments are documented in chronological order to illustrate the experience building process. Firstly, *P. polycephalum* is deployed for algorithmic composition using established Classical Physarum Machine methods. Next, two musical experiments are presented where the organism's electrical oscillatory behaviour is harnessed for sound synthesis and within a composition tool. These three experiments guide the research to Waypoint 2. The chapter then concludes with discussions and reflections on these initial experiments, which lay the ground for the next stage of the research journey.

Below is an overview of this chapter:

- 4.2 - *Physarum polycephalum* Experimental Preliminaries
- 4.3 - Initial Experiments
  - 4.3.1 Experiment 1: Algorithmic Composition with a *Physarum polycephalum* Kolmogorov-Uspensky Machine
  - 4.3.2 Experiment 2: Granular Sound Synthesis with a Biological Oscillator
  - 4.3.3 Experiment 3: A *Physarum polycephalum* Step Sequencer
- 4.4 - Conclusions
- 4.5 - Chapter Summary

4.2 *Physarum polycephalum* Experimental Preliminaries

This section deals with the experimental preliminaries. The aim is to detail the general methods used throughout the research to avoid repetition. Here, information is presented on *P. polycephalum* sample acquisition, culturing and farming practices, safety considerations and disposal, and the techniques used to measure the organism's electrical properties. In regards to the latter, examples aimed at illustrating typical data produced under these conditions are also presented. The accessibility of the consumables and apparatus to creative practitioners is also discussed to begin addressing **RQ3**. The section ends with an overview of the consumables, equipment, and other tools that were used in this research.

4.2.1 Sample Acquisition

Acquiring a sample of plasmodium is not very difficult or costly. As mentioned in previous chapters, over recent years and in line with growing interest in the organism, slime mould advocates have been establishing communities where people can share their experiments, research, and creative practice, one example being the 'Slime Mould Collective'. The members of these communities actively share samples of plasmodium amongst each other for free. Therefore, it is likely that the computer musician who wishes to experiment can acquire a sample from these communities along with advice from experienced users (as opposed to biologists or academic texts).

For the outdoor enthusiast, Adamatzky suggests searching in woodlands for wild plasmodium to use (9). Plasmodia's natural habitat is dark and damp environments where there are plenty of decaying organic material to serve as food. The plasmodium is particularly partial to damp and rotting bark. The *P. polycephalum* strain of plasmodium can be found in the UK and over most of mainland Europe (129). There are several documents available to help novices identify *P. polycephalum* in its natural habitat and collect samples (see (177, 178) for examples). Furthermore, the online communities have several posts that provide insights and advice on foraging for slime moulds.

Perhaps the easiest and most hassle-free method of getting hold of *P. polycephalum* is to purchase a sample from a biological supplier. For this research, specimens of plasmodium were sourced from the Carolina Biological Supply[1] through their UK distributor, Blades Biological[2]. Plasmodium was acquired this way as it provided means of sourcing a consistent strain if more plasmodium was needed. Furthermore, others could repeat experiments using the same sample.

It is not necessary to be an organisation or acquire special registration to purchase plasmodium samples from most biological suppliers. The samples arrived as both living plates and as sclerotium. The sclerotium samples were activated by placing them face down on a hydrated substrate, dripping some distilled water on top, and placing food closely. It normally took 1-2 days for sclerotium to become active plasmodium.

4.2.2 Culturing and Farming

The plasmodium is a fairly robust creature that can be cultured on a variety of substrates. The organism's main growth requirement is humidity. Plasmodia will attempt to migrate on most surfaces if the ambient humidity is high enough. However, to sustain healthy growth for the long-term, researchers typically culture the organism in Petri dishes on non-nutrient agar (1.5-2%), or in plastic containers on damp disposable porous substrates such as kitchen roll (129). Plasmodia will feed on several items of food that are commonly found in the kitchen of UK households (9). For example, Adamatzky found that the plasmodium would feed on foodstuffs such as apples, honey, luncheon meat, and eggs (9). Most biological suppliers, however, distribute samples accompanied by a packet of oat flakes, which is perhaps due to their long shelf life (1-2 years) and low cost.

To produce enough plasmodium for the experiments in the thesis, a farm was maintained adapting techniques put forward by Adamatzky in his instructional book (9). Here, the organism was cultured in round plastic containers that had several air holes drilled into the lid (Figure 4.1). The farm was left in a desk drawer at room temperature. In the initial months of the project, the container was lined with a damp piece of kitchen roll. Every two days the kitchen roll was moistened with distilled water and

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[1] `www.carolina.com` (Accessed: 13 November 2016)

[2] `www.blades-bio.co.uk/` (Accessed: 13 November 2016)

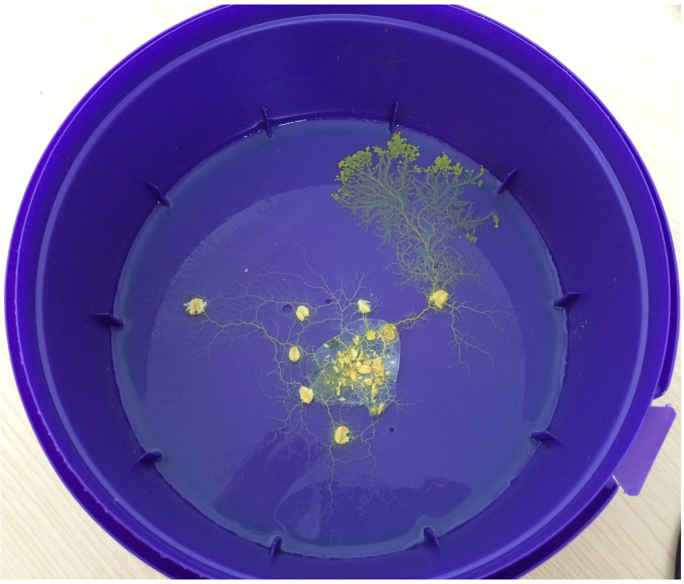

Figure 4.1: A plasmodium farm cultured within a round plastic container on a 2% non-nutrient agar. The farm was fed twice daily with oat flakes and refreshed onto new agar every week.

every week it was replaced. This setup facilitated good growth but after a month or so, on several occasions, the kitchen roll became contaminated. Furthermore, replacing the substrate was a messy task: often the towels fell apart and stuck to the biological material that was removed from the farm. As such, the kitchen roll was replaced with a 2% non-nutrient agar ($\approx$ 7mm thick, which amounted to 100mL). This substrate was much easier to remove and replace. As using pre-prepared agar for the farm would be expensive (approximately £6 for 125mL), agar was made up using powder from Carolina Biological. Again, this consumable can be purchased by private individuals. Alternatively, instead of acquiring agar powder that is especially for use in microbiology, the computer musician could purchase food-grade agar powder, which is cheaper and sold by most health food shops as a substitute for gelatine.

Agar powder was mixed with deionised water sourced from Plymouth University's Microbiology Department: this approach was merely for convenience and to keep costs low. Deionised water is also openly available for purchase. The farm was fed twice daily with oat flakes, and, once a day, cleared of any old or exhausted food sources. The latter process is most important for ensuring the farm remains at low risk of microbial contamination. Once a week the substrate was renewed by removing and setting aside healthy protoplasm, disposing of the old agar, cleaning the plastic container with boiling water, resetting fresh agar, and re-inoculating the healthy protoplasm.

Subculturing the organism into experiment setups involved removing colonised oat flakes or blobs of protoplasm once the farm had been put through at least six hours of starvation. This process lowered the time the organism took to become active in its new environment. Furthermore, protoplasm was always taken from the anterior of the organism, which also promotes speedier growth due to it containing higher quantities of nuclei (129).

There were times throughout the project where farming was paused due to time away and other factors. At these points, plasmodium from the farm was inoculated onto damp filter paper, which was placed in a Petri dish. The dish was left until the filter paper had dried out and the organism had formed sclerotium. This process took anywhere from 2 to 4 days. To start the farm again, the sclerotium samples were placed upside down on the agar, moistened with distilled water, and oat flakes were positioned nearby.

4.2.3 Safely Considerations and Disposal

P. polycephalum is not dangerous. In biological jargon the organism is *'nonpathogenic'*, which means that it is incapable of causing disease (179). Thus, there is no requirement to dispose of excess plasmodium or old dishes through specialist hazardous waste procedures (e.g. autoclave) (179). Microbiological contamination is the main consideration for anyone who is cultivating biological organisms. The work in this thesis was conducted in a non-sterile environment. This is the case for most of the work in UC with *P. polycephalum* due to the vast majority of investigators not having open access to a microbiological laboratory. As such, in this research, nutrient substrates that may have provided potentially harmful contaminants with a healthy growing environment were completely avoided.

For the duration of the project, disposal methods were adopted from (179) where used plates, substrates, and excess biological material were soaked in a solution of 20% bleach for approximately an hour before being placed with the general household waste. It should be noted that plasmodium was very rarely disposed of pointlessly.

Where possible, any excess plasmodium was converted into sclerotium and stored for use later[1].

4.2.4 Measuring *Physarum polycephalum's* Electrical Properties

The experiments in this thesis explore several aspects of the organism's bioelectrical properties. Unless otherwise stated, *P. polycephalum's* extracellular electrical oscillatory behaviour is measured using bare wire electrodes coated in 2% non-nutrient agar and electronically isolated by a non-conductive material (e.g. the base of a Petri dish). The rationale for using this method was its non-invasive nature and low reliance on special measurement equipment. This method was originally put forward by Admatazky and Jones (4) and is now common practice in UC research with *P. polycephalum* (see (119) for several examples). Furthermore, this was the approach adopted in the previous CM project where the organism's behaviour was harnessed for sound synthesis (175).

Electrode quantities and arrangements differed experiment-to-experiment, depending on the CM application. Electrode wire was acquired from RS Components[2] and consisted of 16 0.2mm strands of tinned copper wire. When conducting measurements using this arrangement, it must be noted that the agar is essentially acting as a resistor between the electrode and organism. Studies have found that 1.5mL of deionised agar has a resistance of $\approx$18.5KΩ (180). Therefore, electrical observations will differ as a function of how much agar is coating the electrodes. To produce consistent and comparable results, electrodes were always coated in 1mL of deionised agar, which was precisely measured using a pipette and applied to the electrodes by slowly dripping the liquid over the surface of the wire.

The research in this thesis employs two pieces of electrical measurement apparatus and one voltage source. Here, an ADC-20 high-resolution data logger manufactured by Pico Technology[3] was used for taking extracellular membrane potential measurements. The software that accompanies this device (PicoLog) was used to record bioelectrical behaviour. In all experiments, the data logger was programmed to store the average

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[1] On numerous occasions I found myself distributing samples to inquisitive family members and friends who got interested after asking me about the research.

[2] `http://uk.rs-online.com/` (Accessed: 13 November 2016)

[3] `https://www.picotech.com/` (Accessed: 13 November 2016)

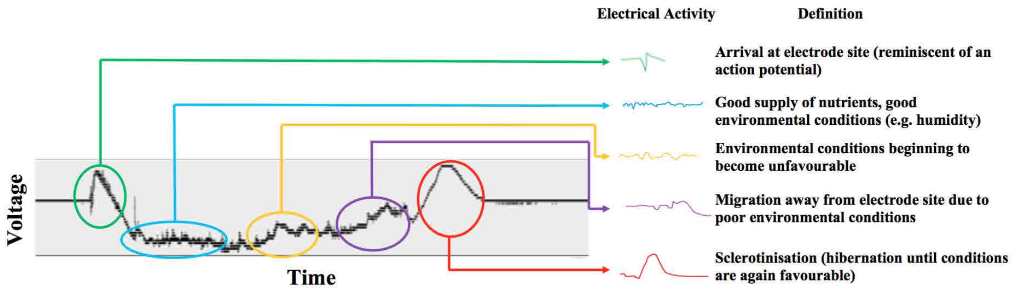

Figure 4.2: Typical example of *P. polycephalum's* electrical behaviour. For reference, a table containing Adamatzky's connotations of the organism's electrical behaviour is included. This is recreated from (4).

of 100 readings from each electrode every second. All CM applications that used bioelectrical recordings were programmed to work with the collation file format of the PicoLog software. Figure 4.2 depicts a typical example of a recording of extracellular membrane potential using the described methods. For reader reference, the figure includes a table of descriptors for patterns in the plasmodium's electrical activities. This table is recreated from Admatazky and Jones's research into interpreting the communicative features expressed in the organism's electrical activity (4, p.15). To produce this data, two electrodes were placed 1cm apart, one electrode was the reference and inoculated with plasmodium while the other had an oat flake positioned on top (Figure 4.3).

Experiments in Chapters 5 and 6 investigate harnessing the organism as an electrical component. For these experiments and the subsequent musical systems, I-V measurements were taken using two pieces of Keithley[1] electrical hardware, which were doubled up in the musical applications. Here, a 617 Programmable Electrometer took current readings while a 230 Programmable Voltage Source sourced voltage. These two devices were interfaced with a computer via ProLogix[2] GPIB-USB controllers using custom software, which was also programmed to provide data logging facilities.

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[1] `http://www.tek.com/keithley` (Accessed: 13 November 2016)

[2] `http://prologix.biz/` (Accessed: 13 November 2016)

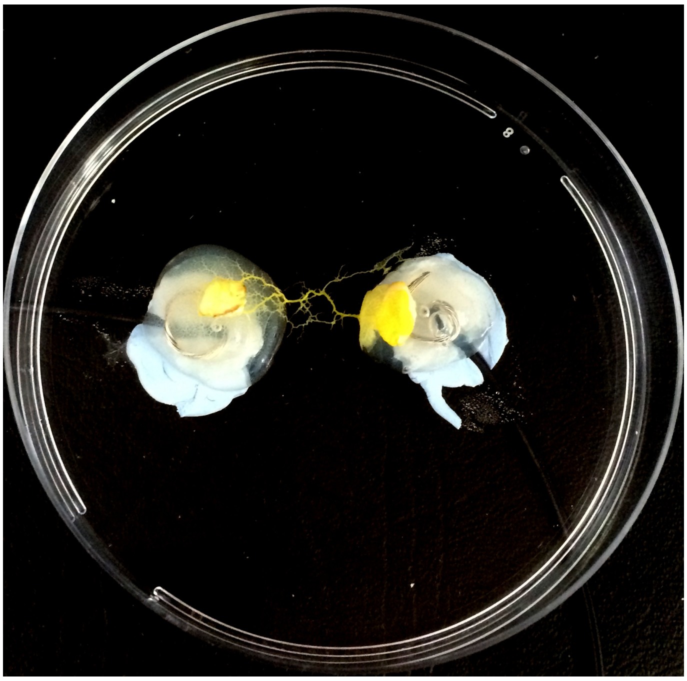

Figure 4.3: A photograph of a typical experimental setup for recording *P. polycephalum's* electrical activity.

4.2.5 Interaction and Control

Forthcoming research explores a number of different methods for interacting and controlling the plasmodium's behaviour. The specifics of these are explained in detail where necessary in the text. This subsection aims to give a high-level overview of these techniques. It is important to note that each of these methods of interaction and control were selected as they have been extensively tested and proven previously.

Although the plasmodium will propagate towards a wide range of different foods, existing Physarum Machine research has proven oat flakes to be an efficient chemoattractant (9). Thus, all experiments used oat flakes as an attractant stimuli to encourage migration.

The research explores using light to interact with electrical oscillatory behaviour. Electro luminous (EL) panels were used as they are inexpensive, produce very little heat, and can easily be placed under Petri dishes. Researchers have used these panels in previous studies of phototaxis in the plasmodium (181). Research by Adamatzky in (120) investigated the impact of white, blue, green, and red illumination on the plasmodium's oscillatory behaviour where it was discovered that certain colours cause unique patterns and dynamics. For example, when stimulated with blue light, it was discovered that the organism's electrical oscillations consistently decreased in amplitude and increased in period. When the blue light source was switched off, the amplitude remained low while the period fell. In these experiments, EL panels were used as the illumination sources.

4.2.6 Software

Throughout this research behaviour is interpreted using custom software that was developed in the visual programming language Max, by Cycling 74[1]. This platform is widely used by the CM research community. In later chapters, Autodesk's 123D Design software is used to develop models for 3D printing.

4.2.7 Overview of Equipment and Consumables

This subsection contains a general overview of the measurement equipment, biological supplies, and other tools that were used for this research.

- Laboratory Consumables
  - Non-nutrient Agar Powder
  - Distilled Water
  - Deionised Water
  - 90mm Glass Filter Papers
  - 60mm Petri Dishes
  - 90mm Petri Dishes
  - 90mm Glass Microfiber Filters
  - Virgin Oat Flakes
- Measurement Equipment
  - PicoLog ADC-20 High Resolution Data Logger
  - Keithley 230 Programmable Voltage Source x 2
  - Keithley 617 Programmable Electrometer x 2

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[1] `https://cycling74.com/` (Accessed: 13 November 2016)

- Other Tools and Consumables
  - Gilson Micro Pipettetor
  - Red and Blue 12v EL Panels
  - Devantech 8 Channel USB Relay Board x 2
  - Lulzbot Taz 5 3D Printer
  - Revolution Science Mini ProBath
  - Single Core Copper Wire
  - M-Audio 410 Firewire Interface
  - Magnetic Resonator Piano (MRP)
  - Yamaha Disklavier Piano
  - 2 Megapixel Digital USB Camera
- Software
  - Cycling 74's Max
  - Autodesk's 123D Design

4.3 Initial Experiments

This section presents three applications of *P. polycephalum's* behaviour for music and sound. The pursuit of these projects was to build practical experience of handling and implementing systems for CM (Waypoint 1). Furthermore, as this was a new area of investigation, it was not yet known how, or indeed if, a biological substrate such as *P. polycephalum* could be used for CM. Therefore, the initial experimental process was also a pursuit to ascertain whether established methods of implementing Physarum Machines could also be harnessed to implement useful systems for CM (Waypoint 2). It is important to note that at this stage of the research, I was not directly concerned with studying the computational properties of the organism. Rather, I was interested in whether the behaviour that renders it interesting and useful in UC could also benefit CM applications. The insights that arose during this process provided the research journey with a bearing to reach Waypoint 3.

Before diving into the initial experiments, let us first recap some of the background information and previous work that the thesis reported on in the earlier chapters. Approaches to implementing Physarum Machines are divided into two categories, Classical and Contemporary (see Section 2.6). The Classical approach is a useful starting point for the UC novice as it provides a method for conducting experiments with little technical knowledge or experience. These approaches were established in the early days of UC work with the organism and look to apply its dynamic topology to various applications through human interpretation of images. As these working methods provided the early pioneers with directions for future work, it seemed logical to use the Classical approach in the initial stages of this research. Thus, as a starting point, an established Classical Physarum Machine framework was adapted for CM. This provided means of gaining practical experience within a music-orientated experiment. As previously discussed, the Classical approach does have a number of drawbacks. These are exemplified by this experiment. Thus, the research journey swiftly progressed onto adopting Contemporary Physarum Machine approaches.

Existing applications of UC in CM have been predominately focused on sound synthesis and algorithmic composition (see Chapter 3). The initial experiments deploy *P. polycephalum* in both these applications. The first experiment investigates how the Classical Physarum Machine approach can be used for algorithmic composition.

Experiment 2 harnesses the organism's electrical oscillatory behaviour for granular synthesis. Finally, Experiment 3 looks at embedding the oscillatory behaviour within a conventional composition tool.

4.3.1 Experiment 1: Algorithmic Composition with a *Physarum polycephalum* Kolmogorov-Uspensky Machine

Finding inspiration to compose a piece of music is eclectic and different for each composer. For example, some composers find their creativity in the observation of nature, in literature, or scientific phenomena. Others prefer to apply algorithms to formalize, or indeed automate, aspects of their compositional processes. The term *algorithm* is derived from the Greek word *arithmós*, which means number, and the Arabic word *algorism*, which means number series. Saitta et al. state that an algorithm *"originally referred only to the rules of performing arithmetic using Arabic numerals"* (182, p.2). Nowadays, the term algorithm does not only refer to performing arithmetics. It can be defined as *"a sequence of instructions carried out to perform a task or to solve a problem"* (28, p.44). Composers have implemented algorithms to aid in the composition of music for many centuries. Thus, it is now considered a long-established method of making music. In Section 3.3 it was suggested that the notion of harnessing natural living systems for musical inspiration is not new. Composers have created music using computer models of living systems for decades. There are little examples, however, where genuine wetware systems have been utilised in algorithmic composition.

Likely one of the most elementary uses of algorithms in composing music is to make decisions on behalf of the composer. Most famously, Mozart employed such techniques in his piece *Musikalisches Wurfelspiel* (Dice Music), where the roll of a dice sequenced fragments of pre-composed music (183). However, the advent of the personal computer has enabled composers to exploit a whole host of processes and rules to make creative decisions. Some examples were presented in Chapter 3. Implementations of Classical Physarum Machines make good use of *P. polycephalum's* decision-making abilities, which researchers have exclusively explored in Refs (184, 185). Thus, Classical Physarum Machines may provide a novel decision-making mechanism for algorithmic composition.

Some level of decision-making is a requirement of all organisms. In the case of *P. polycephalum*, it is making foraging decisions based on optimality theory (184). That is, the organism searches for efficient foraging pathways while balancing environmental dangers with quality of food (e.g. chemical concentrations) (186). Remarkably, researchers have provided evidence that suggests the plasmodium can sometimes behave irrationally (187). Such an ability is normally associated with higher-order organisms that have some kind of serving centre of control (e.g. brain). *P. polycephalum* makes it easy for us to observe its decision-making process because of its unfolding graph-like structure of protoplasmic tubes that connect sources of food. The process of deciding how to sequentially connect elements is reminiscent to how composers have harnessed algorithms in the past. Experiment 1 aims to demonstrate, through an established Classical Physarum Machine approach, that the organism's decision-making abilities can be applied to algorithmic composition.

A consequence of using wetware - living biological entities - for algorithmic composition is chance and pseudo-randomness, which are relatable forms. In algorithmic composition, practitioners often incorporate random processes and chance. An example of such is Mozart's aforementioned *Musikalisches Wurfelspiel*, where pre-composed musical sections were sequenced by the roll of a dice (183). As the plasmodium is an ever-changing living entity, as observers we cannot predict its propagation trajectories with certainty. Furthermore, in some cases environmental factors out of our control may impact the organism's behaviour. For example, food may become infected, causing them to alter classification from attractant to repellent. Thus in using *P. polycephalum* for algorithmic composition, there is an element of chance and pseudo-randomness in the results. Furthermore, it is likely that the sequential experiments using the setup will have varying results.

The proceeding sections give an overview of Experiment 1. Firstly, the established Classical Physarum Machine that formed the basis for the experiment is presented. The next section outlines how these methods were applied in an algorithmic composition system followed by an example of its implementation.

4.3.1.1 The *Physarum polycephalum* Kolmogorov-Uspensky Machine

Blass and Gurevich (188) state that today's conventional computing paradigm, derived from the Turing Machine (31), formalises computation as it is performed by a human and thus may be incompatible with physical processes. In 2007, Adamatzky proposed that a computational model developed by Kolmogorov and his student Uspensky in the 1950s is the mother of all real-life computation (189). He explained that the model formalises computation as if it is performed by a physical process and proposes that the Classical approach to developing Physarum Machines naturally implements a Kolmogorov-Uspensky (KU) machine (189).

A KU machine (190, 191) is an abstract computation model that computes the same class of functions as the Turing Machine (31). However, in contrast to the Turing Machine's tape, a KU machine utilises a finite undirected connected graph with bounded degrees of nodes and labels as its storage structure, which it can reconfigure. The computational process moves on the graph, activating nodes and adding/removing edges in accordance with the program. Only one node can be active at a given time-step, and each node and edge must be uniquely labelled. Thus, every passage from the active node can be described as a string of their unique labels. A fixed radius around the active node is known as the active zone. According to the isomorphism of the active zone, the program executes instructions in the form listed below:

- Add new node with a pair of edges connecting to the active node,
- remove node and its incident edges,
- add edges between nodes,
- remove edges between nodes,
- halt.

Once the program has executed the instructions, the internal state changes accordingly. With his proposal, Adamatzky (189) provided a step-by-step comparison between a KU machine and *P. polycephalum's* behaviour and morphology. Such comparison noted how the KU machine concept is analogous to the plasmodium migrating over an environment while configuring a protoplasmic network between sources of food, which it optimises over time. Detailed below is a summary of his comparison. A visual comparison is also depicted in Figure 4.4.

Active zone: At every time-step there must be an active node. This is a built-in function of the plasmodium: the organism generates waves of tube contraction, which causes a pressure gradient to build up in the tubes. Such pressure results in the periodic movement of protoplasm back-and-forth, changing direction approximately every 50 seconds with greater net flow occurring in the direction of propagation.

Nodes: A *P. polycephalum* KU machine has two types of nodes, stationary and dynamic. Sources of food represent stationary nodes while all other sites where two or more tubes originate represent dynamic nodes.

Edges: Protoplasmic tubes that connect nodes represent edges. A KU machine's storage graph is undirected, e.g. if nodes a and b are connected, then they are connected with edges (ab) and (ba). A *P. polycephalum* KU machine implements this with a single tube but with the periodic movement of protoplasm back-and-forth.

Data input and program: Data input and the program are represented by the spatial configuration of stationary nodes (oat flakes).

Addressing and labelling: *P. polycephalum* does not implement any aspects that provide a direct method of uniquely labelling nodes and edges. Adamatzky suggested and experimented with using food colouring to distinguish each oat flake. However, in this experiment digital labels are superimposed.

Results: The plasmodium halts the computation when all data nodes are utilised —when it has exhausted all available food sources —or when humidity levels are too low for it to continue foraging. When this occurs, the plasmodium enters its dried up dormant state, sclerotium. The result of a computation is the final graph structure formed by the plasmodium's protoplasmic tube network.

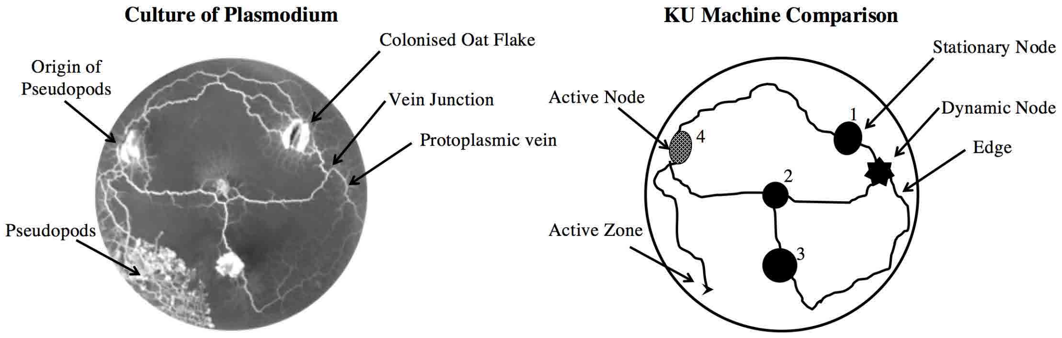


Figure 4.4: A visual comparison of a culture of plasmodium in a Petri dish (left) and a KU machine (right).

4.3.1.2 Applying the *Physarum polycephalum* Kolmogorov-Uspensky Machine in Algorithmic Composition

Adamatzky's formalisation provides a useful framework for interpreting the plasmodium's behaviour in terms of discrete operations; for example, *remove edge* and *add node*. For this algorithmic composition experiment, the KU machine's nodes are seen as musical data that are processed according to the sequential operations performed by the active zone. Such operations are assigned to execute compositional tasks.

Firstly, let us deal with the musical application of the KU machine. Here, each node in the KU storage structure represents a musical phrase, which are uniquely labelled P^1, ..., P^n. The configuration and quantity of stationary nodes (oat flakes) are of the composer's choosing. By taking into account the size of each food source, the composer can weight the likelihoods of migration trajectories: the larger the oat flake, the greater the radius of attraction around the food source. Thus, if two oats are positioned equidistant from the inoculation site, the plasmodium is more likely to propagate towards the larger oat first. The initial position of the plasmodium relative to the stationary nodes will also influence migration direction. The configuration of stationary nodes and inoculation site of the organism defines the Physarum Machine's starting state ($t = 0$). At any given time-step, the composer can position additional nodes into the storage structure. Moreover, as the plasmodium migrates, it may form or remove a dynamic node (a protoplasmic tube junction). In this situation, the dynamic node is assigned a musical phrase and unique label.

Upon the active zone adding edges between nodes, the connected nodes' musical phrases are transformed using a set of composer-defined rules to create a new phrase iteration (P_i^n). These rules can either be universal, unique to each node, or conditional dependent on the isomorphism of the active node's neighbourhood. The respective node's memory is subsequently updated with the new iteration. As a KU machine's storage graph is undirected, both nodes' phrases are transformed, with the destination node being processed first. Once the destination node's phrase has been updated, it places the newly transformed phrase into an output sequence, creating a progressive arrangement of musical phrases. At each time-step that is:

```
ADD_EDGE ($P^a$, $P^b$)
    READ $P^a$
    TRANSFORM $P_i^a$
    UPDATE $P^a$ with $P_i^a$
    OUTPUT $P^a$
ADD_EDGE ($P^b$, $P^a$)
    READ $P^b$
    TRANSFORM $P_i^b$
    UPDATE $P^b$ with $P_i^b$
```

4.3.1.3 Notes on Control

Through the use of stimuli, a composer can restrict access to certain nodes, intensify a node's stimuli gradient, or cause a computation to prematurely halt. However, once positioned in the experimental arena, some of these substances create chemical traces that are difficult to remove. A more dynamic method of controlling behaviour is by using light to obstruct pathways and areas of the experimental arena.

4.3.1.4 Realisation

The results of the biological KU machine are interpreted by human inspection. In this experiment, the human inspection element is coupled with software that provides

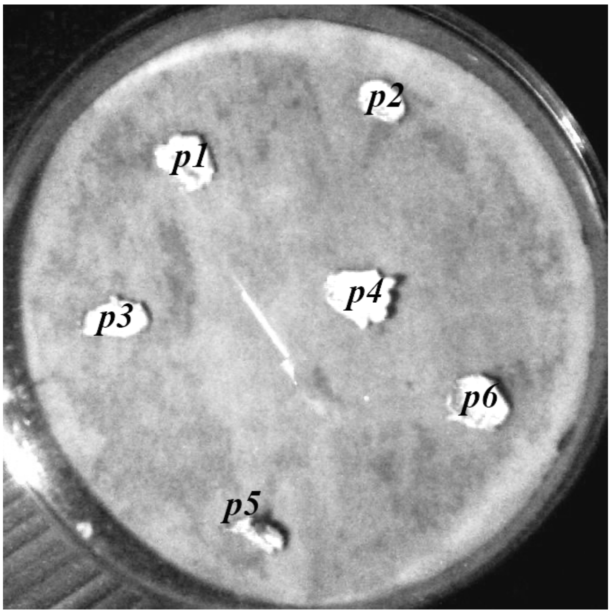
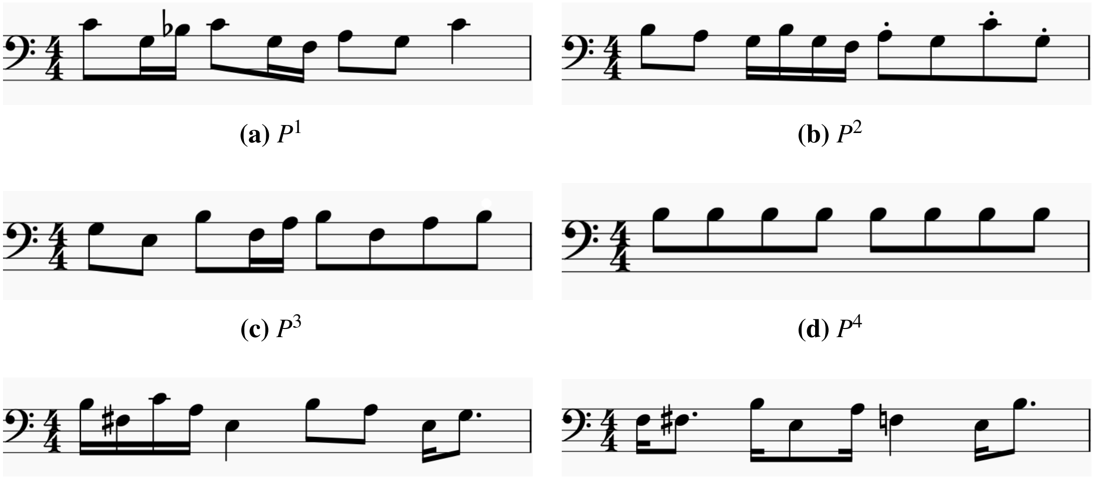


Figure 4.5: A photograph of the experimental space at the start of the experimentation using a KU machine implemented in plasmodium for algorithmic composition.

time-lapse recording facilities and playback along with an interpreter that performs the operations on the musical data.

To experiment with the approach, five oats were distributed (nodes) within 90mm Petri dishes lined with a moistened filter paper (Figure 4.5). A one bar musical phrase was composed for each of the five nodes. By way of creating the active zone and initiating the experiment/computation, the plasmodium was inoculated into the space using a colonised oat flake. As this oat flake also represents a node, it was also assigned a musical phrase. Figure 4.6 shows each node's musical phrase.

The algorithmic composition software is split into two functions, the recorder and the interpreter. The recorder section accepts a feed from a USB camera and allows the user to superimpose unique labels onto nodes within the digital image. Such labels can be added before, during, and after the recording. This allows the composer to label additional stationary nodes and label dynamic nodes as they are created. The software can be set to take snapshots at composer-defined intervals. For this experiment, images were taken every 30-minutes. Once the Physarum Machine had halted, the collated images can be played back as a video for human interpretation.



(a) P^1 **(b)** P^2

(c) P^3 **(d)** P^4

(e) P^5 **(f)** P^6

Figure 4.6: Scored input musical phrases.

The interpreter section requires the user to inform it of the total number of stationary nodes. For each of these, a music phase needs to be input in the form of a MIDI file. By reviewing the collated images, the user then informs the interpreter of the sequential operations performed by the plasmodium at each time-step (e.g. $\mathrm{P}^1 \rightarrow \mathrm{P}^2$). Once input, the software will implement the algorithmic composition. In this example, the interpreter was programmed to transform musical phrases using universal rules, instead of assigning each node individual rules. The rationale here was simplicity, allowing for confirmation of the approach before adding levels of complexity.

The interpreter's rules split each phrase into four sections ($P^n x^1$,..., $P^n x^4$), and transformed each MIDI note value, the delta time between note ons, and each note's duration. The rule compared values within each section against the mean μ of their respective counterpart section. The resulting difference values were then divided by the other section's respective standard deviation σ, and rounded to the nearest whole number. However, if the σ was 0, the software combined both section's phrases and calculated a new σ. Subsequent values were next multiplied by their own section's σ and added to the mean μ, resulting in the transformed musical phrase. That is:

$$[P^a \rightarrow P^b] = \left(\left(\left(\frac{(P^b x_i^n - \mu P^a x^n)}{\sigma P^a x^n} \right) \times \sigma P^b x^n \right) + \mu P^b x^n \right) \tag{4.1}$$

If, however, $P^n x_i^n < 1$ the algorithm replaced the value with the μ of their respective counterpart section.

If the organism added a dynamic node to the storage structure (a protoplasmic tube junction), the system combined the two phrases of the nodes at either end of the edge where the junction originates, and saved this phrase under a unique label P^n. However, if the plasmodium created the dynamic node from extending pseudopods that dispersed in 2+ trajectories, the node was assigned origin node's musical phrase.

4.3.1.5 Results

The experiment took ≈92 hours to complete, with the computation halting as the organism entered its dormant sclerotium phase. The organism entered this dormant phase as a result of it exhausting available sources of food and the filter paper substrate drying out. Table 4.1 summarises active zone dynamics while Figure 4.8 displays a sequence of digitally labelled time-lapse photos. During the experiment, the plasmodium added one dynamic node (P^7) to the storage structure, which occurred at $t = 5$. P^7 was formed from an active zone originating from P^4, which developed pseudopods that dispersed on two different trajectories (Figure 4.7), first arriving at P^3 at $t = 6$, then arriving at P^5 at $t = 8$.

Figure 4.9 shows the algorithmic composition result of the experiment. As the organism created a dynamic node, the algorithm created a new musical phrase (P^7), which was a P^4's phrase at $t = 5$.

4.3.1.6 Discussions

The musical result of this algorithmic composition approach is reminiscent of the pre-composed musical phrases, but with modifications. A common rationale for using algorithmic composition techniques is to aid in the creative process by removing some level of control from the composer. Thus letting the algorithm output materials that, on some levels, is non-deterministic but within parameters determined by the composer. These results fit such a rationale. The final musical material is a result of a union of composer controlled elements, such as pre-composed musical phrases, transformation rules, and experimental setup; as well as non-deterministic elements such as organism propagation trajectories and the addition of dynamic nodes.

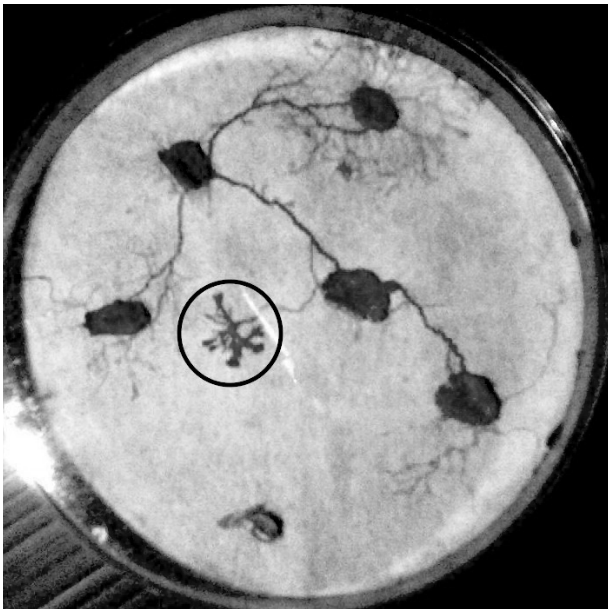
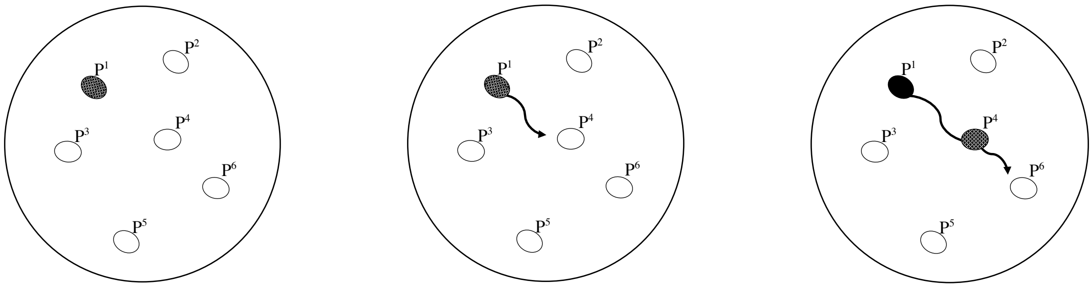


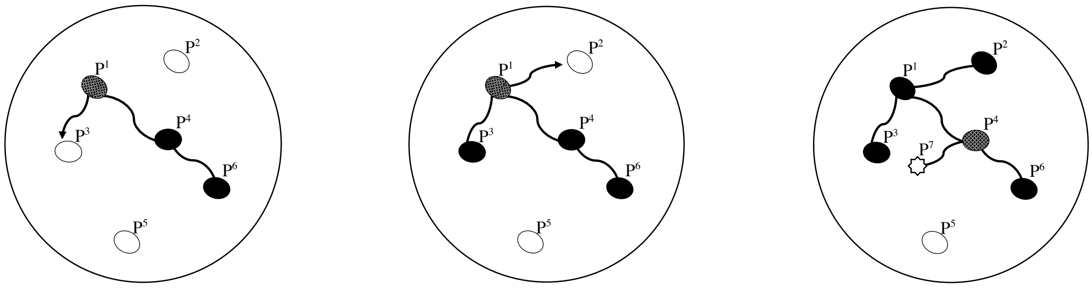
Figure 4.7: A photograph of $t = 5$. Here, the active zone added a dynamic node to the storage structure by forming pseudopods that dispersed on two different trajectories

Time-step	Origin Node	Destination Node
1	P^1	P^4
2	P^4	P^6
3	P^1	P^3
4	P^1	P^2
5	P^4	P^7
6	P^7	P^3
7	P^3	P^5
8	P^7	P^5
9	P^5	P^6

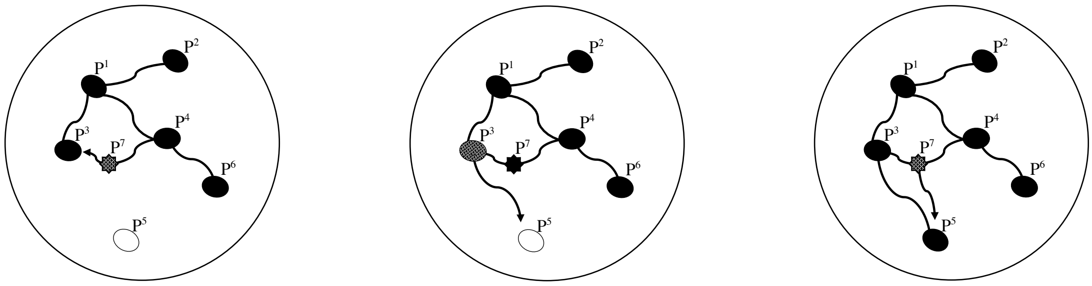
Table 4.1: Table describing the active zone movements during the experiment.



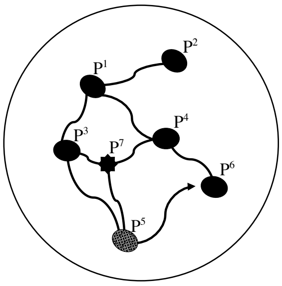
(a) $t = 0$ **(b)** $t = 1$ **(c)** $t = 2$



(d) $t = 3$ **(e)** $t = 4$ **(f)** $t = 5$



(g) $t = 6$ **(h)** $t = 7$ **(i)** $t = 8$



(j) $t = 9$

Figure 4.8: An overview of the experiment with the *P. polycephalum* KU machine, depicting the active zone dynamics described in Table 4.1. These illustrations are of the experimental setup shown in Figure 4.5. (f) shows the time-step when the plasmodium added a dynamic node to the storage structure, which is also shown in photograph form in Figure 4.7.

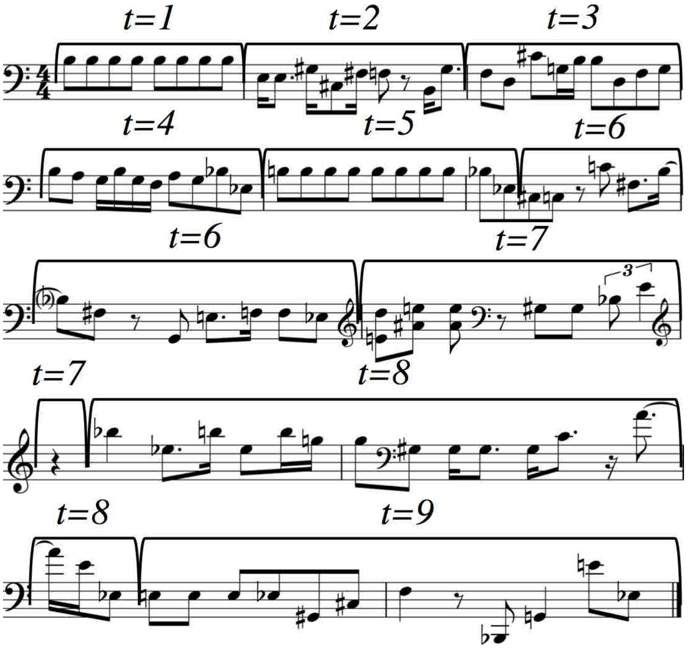



Figure 4.9: The musical result of the experiment.

4.3.2 Experiment 2: Granular Sound Synthesis with a Biological Oscillator

Although the seeds of Granular Synthesis (GS) can be traced back to the 17th century (192), British physicist Dennis Gabor postulated the notion of a granular theory of sound in the 1940s (193, 194). His theory, entitled *'acoustical quanta'*, views sound as the combination of myriads of sonic particles known as grains. Gabor believed that a granular representation could describe any sound. Sound grains are very short sounds that are on the cusp of human auditory perception (typically 1-100milliseconds) (146).

In GS, grains serve as building blocks to create larger sound objects, which often consist of hundreds, if not thousands, of sound grains. Each grain is a waveform that the composer shapes with an amplitude envelope of their choosing. The way a composer approaches grain organisation defines the sonic outcome. Miranda suggests that there are three general approaches to GS: sequential, scattering, and granular sampling (195). The sequential approach works by arranging individual grains into an order where no grains overlap. This approach requires only one grain generator and allows the composer to control grain length and the Δt between grains. The scattering approach uses several generators to scatter grains over a set period of time. Such grains can overlap and may be synchronous or asynchronous. Composers often refer to the sonic result of this approach as *'sound clouds'* (146, 192). Unlike the previous two approaches, granular sampling creates sound grains from pre-recorded source material. Here, the grain generators sample the material and apply an amplitude envelope to produce the grains. The generator may randomly choose where in the source material it addresses to create the grain or it may be defined by the composer. There are several methods of building sound objects with this approach. For simplicity, the grain generator may just produce one grain that it loops at a certain speed. Composers can achieve more complex results by developing custom algorithms. For example, the grain generator may randomly create grains from a selection of different source material that it organises using the sequential or scattering approach.

As the three aforementioned approaches indicate, composing with GS can be extensive and a sonically detailed process. Compositions that conform to conventional musical theory have a temporal hierarchy of structure. Part of the compositional process is managing the interaction between structures on different time scales —from individual note level to the topmost level of a complete composition. When composing with GS, however, there are additional levels that go below note level to grain level. At grain level, there is a massive quantity of control data required to advance to higher perspective sound levels. For example, if each grain has n quantity of parameters (these often exceed double digits), and there is q amount of grains in a second long sound object, then n multiplied by q equals the amount of data needed to produce a second of audio (146). As such, composers wishing to adopt GS in their works often require algorithms that produce grains in accordance with global parameters.

Experiment 2 explores how the plasmodium's extracellular membrane potential may be used as the source material within a GS instrument. This application of the organism's behaviour can be seen as an extension of the previous work into harnessing *P. polycephalum* for CM (presented in Section 3.4.2). To recapitulate, in this project the organism's electrical readings were recorded and subsequently scaled to control the frequencies and amplitudes of a group of oscillators within an additive GS framework. However, results were hampered by the quantity of data generated by recording the organism's electrical activity. Such large amounts of data were compressed to render them usable, which was to the detriment of the relationship between the sound and the

Figure 4.10: The growth environment for the granular synthesiser.

behaviour of the plasmodium. This experiment looks to develop another approach to harnessing electrical behaviour by regarding it as a granular audio oscillator, whose behaviour can be controlled via optical stimulation.

4.3.2.1 Methods

Due to *P. polycephalum* taking several days to span an environment, custom software was designed that implements the GS algorithm over the duration of the organism being active and in accordance with composer-defined parameters. The software takes 100 samples from each electrode every second, which are then averaged to produce a single reading per second. In this experiment, each electrode site is considered a granular audio oscillator. Therefore, the composer can control the quantity of grains by placing additional electrodes into the growth environment. Currently, the GS software is programmed to accommodate up to eight electrode inputs, which can be easily expanded as necessary. Figure 4.10 shows an experimental growth environment for Experiment 2. Here, four electrodes are arranged on the vertices of a square, with a reference electrode positioned in the centre.

The software transcribes each of the electrodes' measurements into audio buffers at a sample rate of 44.1 kHz. At composer-defined intervals, each buffer is addressed

Figure 4.11: Four sample images of the plasmodium's behaviour within the growth environment depicted in Figure 4.10.

to produce a sound grain, which are sequenced together to produce one sound grain per interval. Grain lengths are determined by scaling each electrode's potential difference value against the current average of all other electrodes, to a global minimum and maximum grain length range that is specified by the composer beforehand. The software limits this range to 10-100 milliseconds. Each electrode's buffer is only addressed for grain creation if the organism is active in the respective area. The software achieves this by reviewing each incoming measurement for oscillatory activity. Once initiated, the software automates the GS composition until all food sources have been exhausted and the plasmodium starts to fructify or progress into its dormant sclerotium phase. Upon conditions being met, the system halts and renders the resulting audio file. For user reference, the software can also take snapshots of experiments at specified intervals (see Figure 4.11 for examples).

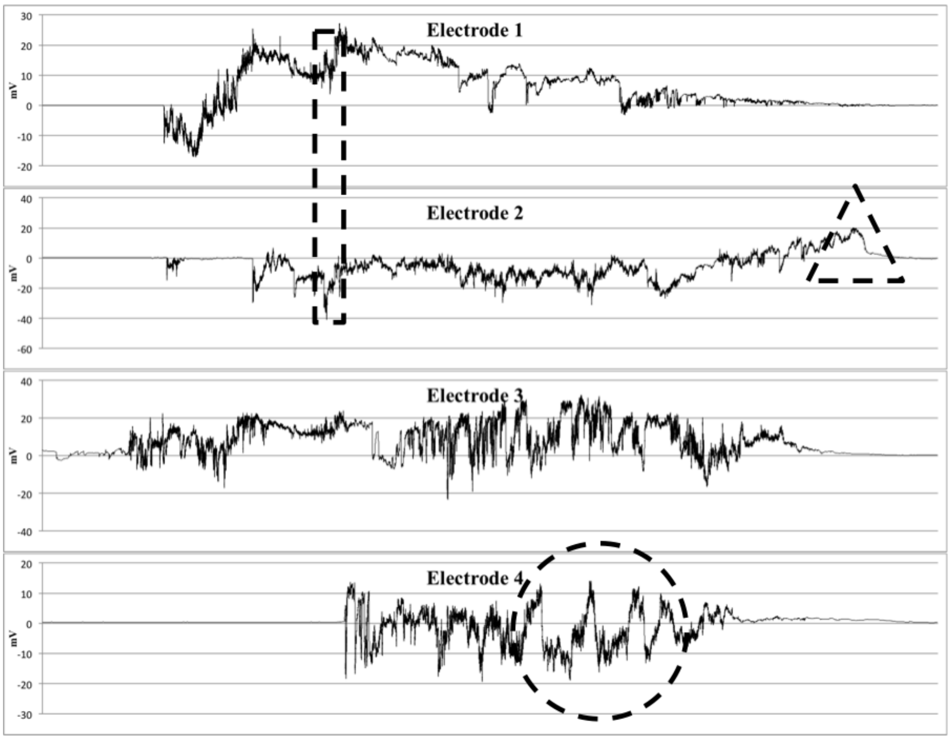


Figure 4.12: Graphs depicting the electrical activity within the growth environment shown in Figure 4.10. Each line plot corresponds to the activity recorded on one of the electrodes.

4.3.2.2 Results

Considering that the growth environment depicted in Figure 4.10 illustrates a typical example of conditions for the plasmodium to forage in, on average it takes five days for experiments to complete. Shown in Figure 4.12 is a set of graphs denoting the typical electrical activity produced by the setup depicted in Figures 4.10 and 4.11. First, the plasmodium gradually propagates from the centre electrode to the measurement electrodes, which took two days to occur. When the plasmodium arrives at an electrode's site, readings show a quick rise followed by a sharp drop in potential. A clear example of this can be seen on electrode 4 in Figure 4.12. Colonisation happened first at electrode 3, next at electrode 1 followed by electrode 2, and, finally, electrode 4.

Propagation to each electrode came equally from the central inoculation electrode as well as neighbouring electrodes. This propagation behaviour configures a protoplasmic tube network that connects each of the colonised regions together. The resulting morphology impacts the electrical activity measured by each electrode. This is because of the cellular waves of contraction and relaxation that interact and proliferate across the organism. Such activity can result in a series of impulses that can spread a distance across the organism, according to the amplitude and conditions at other colonised regions. An example of which can be seen on electrodes 1 and 2 (marked by the rectangle). The sclerotium phase is characterised by an increase in voltage (marked by the triangle). In this example, a red EL panel was used to alter the organism's oscillatory behaviour. The effect of this can be seen on electrode 4 where 3 periodic bursts of light have caused spiking and an increase in amplitude (marked by the circle).

Shown in Figure 4.13 is a cochleogram of the granular piece produced by the system from the setup in Figures 4.10 and 4.11, and graphs in Figure 4.12. In this example, the system generated 174 seconds of audio material from five days of plasmodium electrical activity. Notice the dark lines in Figure 4.13 and how they are morphologically related to the electrical plots displayed in Figure 4.12.

4.3.2.3 Discussions

An audio example of this experiment can be found on Appendix 1. This approach to GS with *P. polycephalum* is useful for the composer wishing to use granular synthesis as it automates the production of grains. Furthermore, the sonic result can be fine tuned by taking advantage of the organism's innate taxis response to various stimuli, which was exemplified in the above example. Composers can also create different audio densities and output lengths by creating different electrode arrangements. Currently, this approach to harnessing the organism takes several days to generate a few minutes of audio, which can make its employment tedious.

4.3.3 Experiment 3: A *Physarum polycephalum* Step Sequencer

Experiment 3 is a follow-up version of a basic proof-of-concept system that was developed during my master's degree at Plymouth University. Step sequencers are software or hardware devices that loop through a specific quantity of steps at set time intervals, commonly defined in beats per minute (BPM). Each step can normally exist in one of two states: active or inactive. When active, a predefined sound event will trigger as the sequencer reaches its respective position in the loop. Conversely, no sound is produced

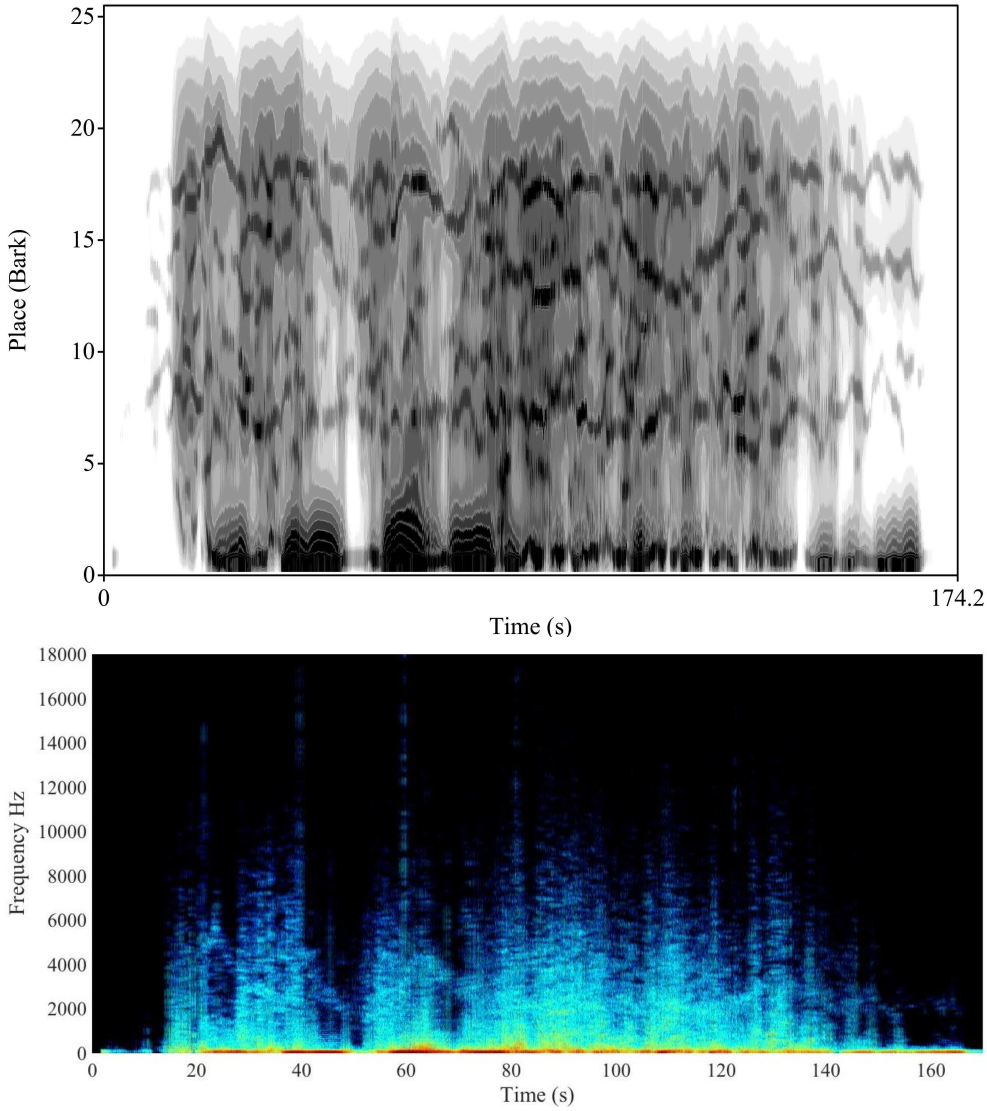


Figure 4.13: Cochleogram (top) and spectrogram (bottom) of the result of using *P. polycephalum's* electrical oscillations for GS.

when the step is inactive. It is common for steps to be associated with several parameters that allow the programmer to add musical expression: for example swing and velocity, to cite but two. Step sequencers are a very popular tool in music production and come as a standard feature in most DAWs. Perhaps their most prominent application is sequencing rhythmic sections (e.g. drums and bass), which is due to their rigid structure.

The *P. polycephalum* step sequencer adapts ideas from both Classical and Contemporary Physarum Machines where the organism's migration behaviour and fluctuating electrical potential automate the tool's parameters. The rationale for implementing such a device was to combine the successes of the previous two experiments to create a tool for composing music. To recapitulate, Experiment 1 demonstrated how the organism's ability to form and reconfigure connections between sources of nutrients could be used as a method of decision-making in algorithmic composition. Although this application could yield interesting arrangements, the behaviour played little part in the sound of the music. The transformation rules and pre-composed material were the integral factors in the system's output. As such, composers could achieve similar and more instantaneous results by substituting the plasmodium in favour of programming a conventional computer to make the decisions. For example, by implementing random walk algorithms in multi-agent systems. For many composers, this is likely to be more appealing as it circumvents the lengthy process of growing the organism and interpreting its behaviour manually. Moreover, it could provide means of interacting with the system in real-time. Therefore, to begin addressing research questions **RQ2** and **RQ3**, more useful applications of the organism's behaviour needed to be established. Indeed, if there were a way of harnessing the creature's ability to form and adjust its protoplasmic network without having to interpret data manually, then the musical possibilities would be far greater.

Experiment 2 demonstrated that the organism's rich spectrum of electrical oscillations could provide the source material for a granular synthesiser, and, to some degree, could be controlled to create variations in sound. However, the sounds created by this application are not likely to be appealing to all composers, and the system could not generate sound in real-time. During this experiment, however, it was noted how spikes in the organism's electrical activities would proliferate from one electrode to another according to both the configuration of the protoplasmic network and the amplitude of the spike. This phenomenon resulted in sequences of impulses being registered at different electrode sites in varying sequences over time. Resulting from this observation, a step sequencer was conceptualised where *P. polycephalum* controlled step activation through propagation trajectories/colonisation, and sound event triggering with fluctuating levels of electrical activity. Thus, the *P. polycephalum* step sequencer applies both the migration and bio-electrical behaviour in a musical tool.

Bio-electrical oscillations are of very low frequencies, which limits the feasibility of harnessing this behavioural aspect with a live culture of plasmodium. Therefore, to implement a sequencer that can be used in real-time, behaviour needed to be gathered from an experimental process beforehand. This approach is potentially limiting in respect of interacting with the organism's behaviour. However, the software tool can provide other means of real-time interaction, which goes towards answering **RQ2**.

4.3.3.1 Growth Architecture Design

In order to implement the step sequencer, an appropriate growth environment was designed. Here, the electrode arrangement mimicked the architecture of a step sequencer, which is schematically shown in Figure 4.14. It consisted of a Petri dish divided into six electrode zones, representing sequencing steps (S_1, ..., S_6), arranged in a circular fashion with a central inoculation area (C). This 360° design mimics a sequencer loop, and gives each step equal weighting in the sequence. To entice propagation and promote colonisation in each zone (step activation), an oat flake was positioned in the centre. This was also extended to the inoculation area to create an initial central node that can propagate in any of the six directions throughout the experiment, increasing the chance of steps becoming active in a non-sequential order. Furthermore, this arrangement encouraged the organism to reconfigure its protoplasmic network as it foraged around the circle. Photographs of the step sequencer growth environment are shown in Figure 4.15.

4.3.3.2 Results

Before presenting the software side of this application, let us first review a typical example of the organism's electrical behaviour in the step sequencer growth environment. Here, the data logger was set to sample each electrode 100 times per second and then

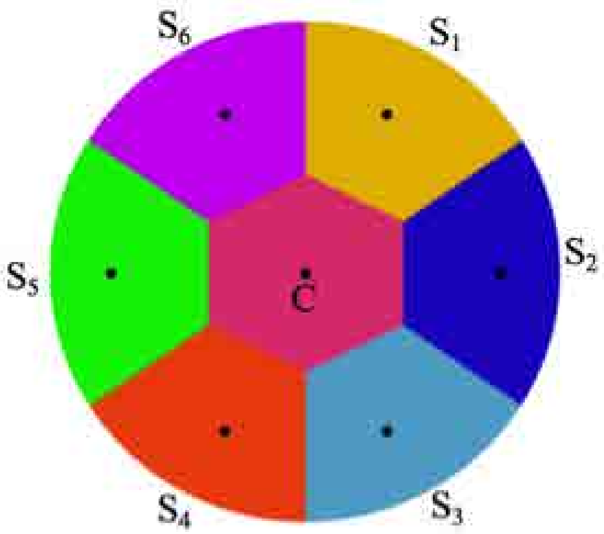


Figure 4.14: A scheme of the *P. polycephalum* step sequencer growth architecture.

Figure 4.15: Photographs showing the construction of the environment for the step sequencer. Shown on the left hand side is the bare-wire electrode array wired into position. The right hand side shows the completed growth environment with each electrode embedded within blocks of agar.

average the readings to produce a single value for every second. In tandem, custom software took image snapshots at intervals of 5 minutes with white LEDs turning on 5 seconds before image capture and staying active for 10 seconds.

In this example, the data collection process took just under five days to complete and was halted as the plasmodium entered its dormant sclerotium phase. This occurred as a result of a drop in humidity as the agar substrate dried out in conjunction with a lack of nutrients as food sources within the environment became exhausted. The collection process generated an excessive quantity of electrical potential data: circa 330000 entries for each measurement electrode. Harnessing this quantity of information in the device would result in extremely long sequences of sounds. In order to circumvent this, a compression algorithm was applied to the data. From a musical intention point of view, it was important that time-based meaning and relevant gradients between behavioural patterns were maintained. Here, data was viewed as sets of readings for each second. First, the quantity of measurements was reduced by combining blocks of ten entries and averaging their measurements, leaving a single entry for $e_1 ... e_6$. The subsequent data was then processed as follows: readings at time t are only withheld from removal if two measurements from $e_1 ... e_6$ present a change over a set threshold (b) from their counterpart within the previous set of readings (t^{-1}). This is expressed in the following where if $_x$(S) = 1 the entry is withheld, otherwise it is lost:

$$\sum_{i=1}^{6} x(|e_i^t - e_i^{t-1}| \geq b) \geq 2 \tag{4.2}$$

Here, i is one of the six electrodes, t represents a set of electrode readings at a given time, and b is the minimum change threshold.

This compression stage reduced the quantity of entries to circa 5500, while maintaining behaviour patterns and the voltage gradients between them. Figure 4.16 shows line plots of the electrical activity on each measurement electrode after compression.

In this case, it took the organism just under 12 hours to propagate from the central inoculation area to a sequencer step. When the plasmodium arrives at an electrode, a fast change in voltage is registered, which in these results is an increase ranging from 5 ± 15mV. Propagation to each step came equally from both the central node as well as neighbouring steps. Activities and conditions within colonised regions cause differing intracellular activity, which in turn can result in electrical impulses across

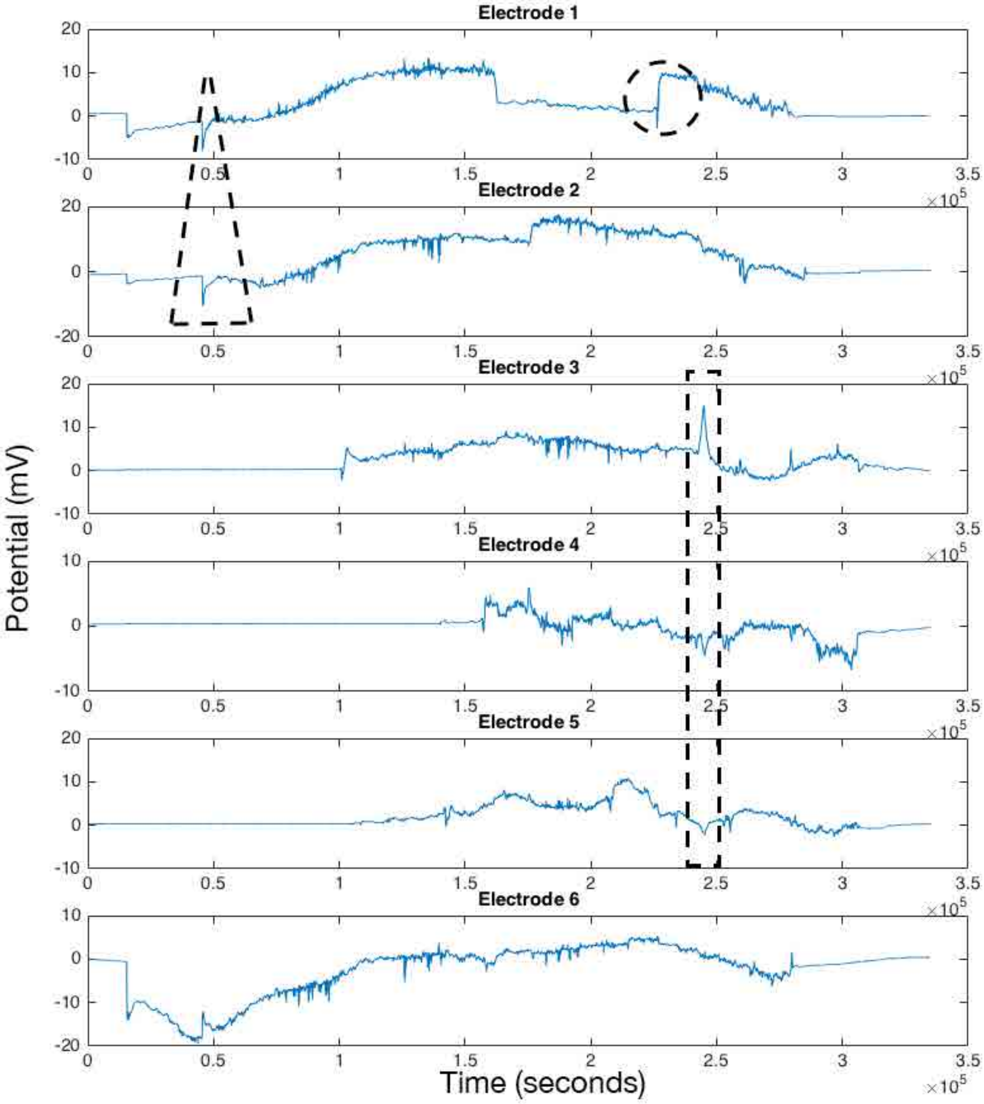


Figure 4.16: Line plots depicting the electrical behaviour of the plasmodium within the step sequencer growth environment shown in Figure 4.15.

the organism. Such impulses are typically registered in regions connected directly, but may spread a distance across the organism if conditions are favourable (electrodes 3, 4 and 5 in Figure 4.16, marked by the rectangle). When arriving at two electrodes at the same time, electrical readings exhibit synchronised patterns. This is the case for electrodes 1 and 2, as shown by the triangle. The sclerotium phase is marked by a circle on electrode 1.

4.3.3.3 Step Sequencer Software Design

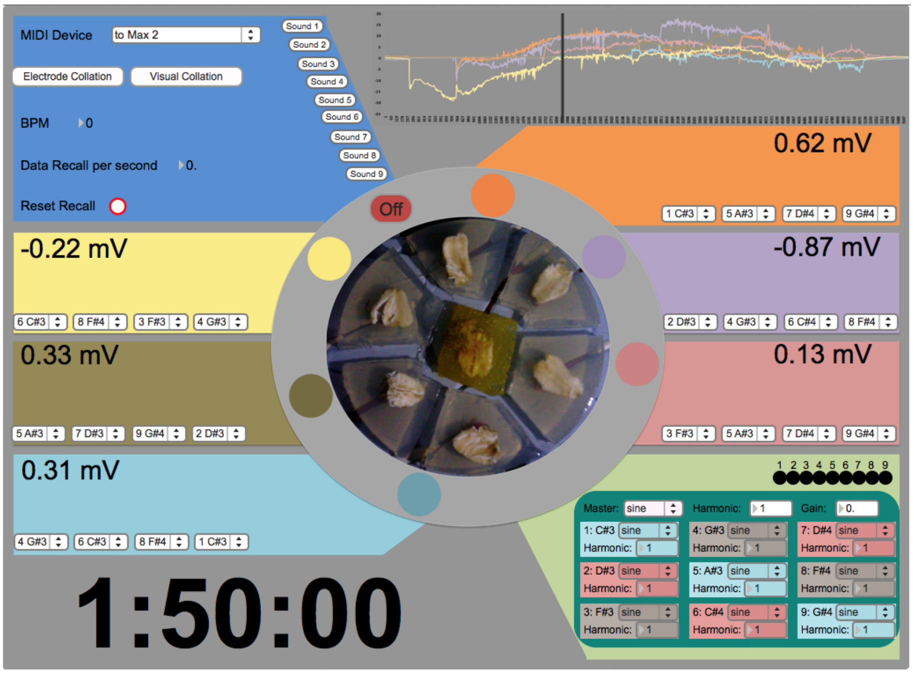
The step sequencer application was primarily implemented in Max with some data handling operations being dealt with in Javascript. The system functions by recalling the recorded behaviour from a text file at a user-specified speed, defined in readings per second. This parameter allows the user to define the dynamics of each step's musical event triggering over time. A low recall speed is likely to result in slow changes as there may not be a substantial difference between a step's successive readings. For example, the user may recall the data at the recording rate, which will result in sound events changing as a function of the organism's natural oscillation frequency and amplitude. Conversely, when the user specifies a high recall speed, readings will modulate quicker. Each measurement is adjusted to become an absolute value once it has arrived into the application. This modification standardises the measurements to allow for mappings to be made according to the measurement's distance from zero.

Once the user has specified the data recall settings, the step sequencer can begin to generate an output. Each of the six measurement streams is assigned to a sequencer step. The device functions by stepping through each electrode's measurement taking a sample at a user-defined BPM. This parameter defines the tempo of the output. Furthermore, if the user considers the data recall rate, the BPM speed can also help dictate sound event dynamics. Each of the six steps only become active when the plasmodium has arrived at the respective electrode site in the behavioural recording. Sound events are not triggered by a step until it has been activated. The electrodes register a sharp change in potential upon the plasmodium's arrival at their site. Therefore, to achieve automatic step activation, each of the six data streams are gated. Once a step's gate is opened, the system monitors the incoming readings for oscillatory behaviour in order to retire steps from triggering sounds when the organism is no longer active at the electrode site. Here, the system monitors the standard deviation for the previous 50 measurements. Assuming that the data was gathered from each electrode at a rate of one measurement per second, this analysis window size corresponds with the lower value of the organism's oscillatory periods (as defined in Section 2.5.2). This window size is also adequate for analysing compressed data sets. If the standard deviation falls below a predefined threshold the gate closes and the step is no longer active.

The magnitude of each step's reading is quantised into one of four voltage triggering ranges, which are associated with a user-defined sound events. There are two options available for the user to define the nature of this procedure. The first is to allocate the quantisation ranges locally where the system retrieves the minimum and maximum values for each individual electrode. Conversely, the second option is to allocate the ranges globally where the application retrieves the highest and lowest values across entire recorded data set.

The user interface is an integral part of any musical device. In this case, the interface was designed to create a connection between the device's output and the behaviour of the organism. To achieve this, when importing the recorded electrode data, the system will also ask for the file directory of the time-lapse images. Using the data recall speed, the sequencer calculates the correct frame rate to ensure the images are played back with perfect synchrony to the electrical readings. These images are featured in the centre of the user interface. Each step's parameters are positioned next to its corresponding agar blob, which creates an intuitive link between the software and the wetware. The interface (Figure 4.17) also provides an interactive graph showing an overview of the combined electrical potential readings (on the top right hand side), which is auto generated upon the user importing the recorded electrode data. This allows the user to change the current position of the data being recalled, creating means to restructure the output of the sequencer.

Using the described framework, two variations of sequencer application were developed to probe its usability in realistic musical production. One of these versions looked at harnessing the plasmodium's behaviour to extend the functionality of a conventional step sequencer by triggering different sounds as a function of each step's electrical potential readings. Here, the system allows the user to import four sound samples to each step. In this case, each step's readings are used to trigger one of the four sound samples; e.g., sound x would be triggered with voltage values between 0


MIDI Device: to Max 2
BPM: 0
Data Recall per second: 0.
Reset Recall ○

-0.22 mV: 6 C#3, 8 F#4, 3 F#3, 4 G#3
0.33 mV: 5 A#3, 7 D#3, 9 G#4, 2 D#3
0.31 mV: 4 G#3, 6 C#3, 8 F#4, 1 C#3
0.62 mV: 1 C#3, 5 A#3, 7 D#4, 9 G#4
-0.87 mV: 2 D#3, 4 G#3, 6 C#4, 8 F#4
0.13 mV: 3 F#3, 5 A#3, 7 D#4, 9 G#4

1:50:00

Master: sine
Harmonic: 1
Gain: 0.
1: C#3 sine, Harmonic: 1
2: D#3 sine, Harmonic: 1
3: F#3 sine, Harmonic: 1
4: G#3 sine, Harmonic: 1
5: A#3 sine, Harmonic: 1
6: C#4 sine, Harmonic: 1
7: D#4 sine, Harmonic: 1
8: F#4 sine, Harmonic: 1
9: G#4 sine, Harmonic: 1

Figure 4.17: The step sequencer user interface.

mV and 15 mV, and so on. The other version took the form of a MIDI instrument. Here, the recorded behaviour is put through a musification model where the user can change the parameters. In this version, readings taken by the sequencer are used to trigger a set of nine MIDI notes that are programmed in by the user. All steps are allocated a set of four notes from the nine available, which are then each assigned to one of the four voltage ranges. When a note is triggered, its velocity is produced through scaling the step's current electrical potential value to the MIDI data range (0-127). In order to determine the duration of a note, the system calculates the current mean potential of all other steps (active and non-active) to produce a mean potential difference value. The higher this value, the more significant the note's duration will be within the sequence, with a maximum duration being four beats (calculated in accordance with the specified BPM). The sequencer is limited to only allow six notes to sound at a time; if a note is triggered but is unavailable due to being made active by another step, the note with the closest value in the step's priority list will sound. For example, if a middle C note is triggered by step two then three but step two's duration is longer than one beat, step three will round its reading to the next closest quantise region and trigger the respective sound event. To make this version of the sequencer versatile, the user can alter each step's note priority order in real-time.

4.3.3.4 Musical Results

In both scenarios, the output of the step sequencer produced a variety of interesting arrangements, which can be used by composers in several different ways. In the sample-triggering scenario, it was found that by allocating sounds to a relative voltage range —for example, higher velocity sounds to elevated voltages —a naturally progressive output is achieved. Such an output is exemplified by the left-hand side radar graphs in Figure 4.18. However, at certain points, the sample arrangement became slightly repetitive (Figure 4.18, right-hand side). From a musical perspective, the MIDI scenario appeared to produce more useful and interesting results. This version of the device outputs a progressive arrangement of notes, which corresponded morphologically to the recorded foraging behaviour. As a musification of behaviour, the produced output does convey auditory representation of voltage levels quite accurately. This is because each note's velocity is produced directly by the respective step's voltage —a parameter that directly relates to energy. Moreover, by producing each note's duration with a potential difference value, it is possible to compare activity on each step through listening. From a musical perspective, having note velocity controlled this way was slightly un-dynamic due to voltage levels also controlling which notes are triggered: each note is played with a similar velocity every time. As a compositional tool, it was found that this version of the sequencer was useful for arranging sets of pre composed notes and applying interesting variations over time.

The MIDI version of the *P. polycephalum* step sequencer was featured in The Creeping Garden feature-length documentary (196), where part of the film's sound track was composed using the tool.

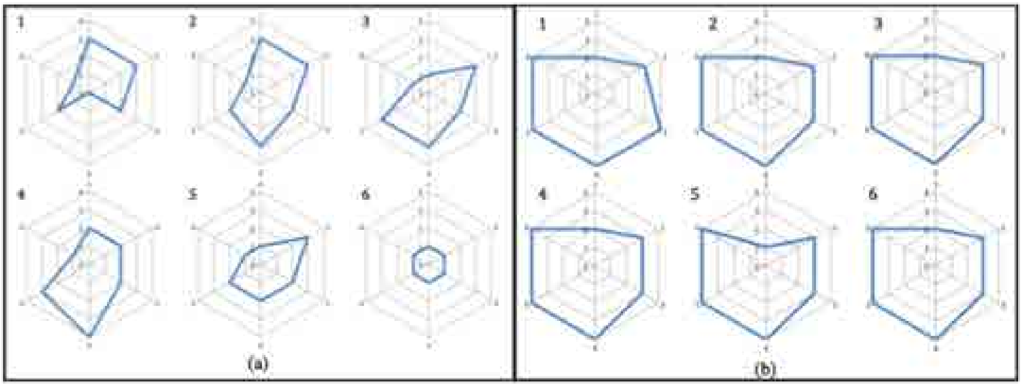


Figure 4.18: Radar graphs depicting two sets of six consecutive sequencer loops. Set (a) shows the sequencer's most dynamic arrangement, while (b) shows a repetitive arrangement.

4.4 Conclusions

The previous sections presented three sequential experiments that were the initial stages of this research's journey. Although these applications had their limitations, they do provide crucial insight into developing CM systems with *P. polycephalum* and allow us to begin addressing **RQ1 —RQ3**. It is important to note that these experiments were not in direct pursuit of developing applications that were fit for mass consumption in CM. Rather, the experiments made up a process to allow for the accumulation of experience and knowledge regarding how to use the organism for CM (Waypoints 1 and 2). It was expected that such experiments may produce some negative answers to the research questions. This is, however, a crucial part of the research journey as we need to establish how these types of UC computers may provide new tools or enrich established tools in CM.

Firstly, it is apparent from Experiment 1 that the Classical Physarum Machine approach is not compatible for real-world CM applications. Indeed, as a result of the organism's slow migration, there is limited scope for implementing real-time musical system that use Classical Physarum Machine approaches. Furthermore, the methods require human interpretation of results, which is a tedious process that is likely to deter the vast majority of computer musicians. It would be possible to circumvent the human-dependency of Experiment 1 using image processing techniques. However, this would be a significant feat in terms of programming, which is likely to take a lot of time to do with no real impact on the musical result.

It is important to note that Experiment 1 harnessed the plasmodium to make decisions. The nature of the output was down to the transformational rules and pre-composed musical segments: both of these elements were created irrespective of the plasmodium. Therefore, it is likely that similar and more instantaneous results could be achieved by substituting the live plasmodium for a software-based decision-making mechanism (this could be a computer simulation of the organism, for example). Nonetheless, Classical Physarum Machines may have some applications in music. It is likely that these methods will appeal most in situations where speed does not matter. One example may be a contemporary composer who is looking for inspiration for a unique composition where the music is scored beforehand so there is no reliance on using plasmodium during the performance. Thus, in regards to **RQ1**, Experiment 1 demonstrated that Classical Physarum Machines are not well-suited to CM.

The problem of speed was also present in Experiment 2 where the plasmodium's bio-electrical activities were used as the source material for a granular synthesiser. This system took five days to generate under 200 seconds worth of audio data. Although the lead time was considerable, this application of behaviour may provide the CM community with a method of automating the production and spectral distribution of sound grains in GS. Irrespective of speed, such a method is simple to implement and the sonic result can be altered through various means of stimulation (e.g. light and chemicals). Moreover, when interacting with the bio-electrical behaviour at individual granular oscillator level, activity at other electrode sites change in amplitude and frequency. Thus, the spectral arrangement of grains takes advantage of the organism's ability to organise its global oscillatory behaviour. Such behaviour allows us to begin addressing **RQ3**.

Finally, Experiment 3 explored methods to overcome the speed issue in order to work towards implementing musical tools for real-time use. Here, instead of using the organism live, offline recordings of electrical behaviour were embedded within a step sequencer device. The idea behind this device was to combine the successes of the previous two experiments: decision-making and the organism's rich spectrum of electrical oscillations. Two versions of the sequencer were developed to probe how the device may address **RQ1**.

From these three experiments it can be confirmed that *P. polycephalum* exhibits properties that can be harnessed to implement systems for sound synthesis and musical composition. However, it is apparent that the research needs to progress past methods of implementing Physarum Machines that cannot be embedded into systems for use in real-time.

4.5 Chapter Summary

The purpose of this chapter was twofold. Firstly, it introduced the experimental preliminaries of acquiring and farming the plasmodium of *P. polycephalum*, thus progressing the research journey towards Waypoint 1. It also introduced an overview of the experimental methods and equipment that is used throughout this research. Secondly, the chapter presented the initial CM experiments with *P. polycephalum*. Such experiments were in line with the metaphor of a journey (as explained in Section 1.4); they were designed to build experience and provide insight into how the organism may be useful for CM (Waypoint 2). At this point of the research, it could be confirmed that *P. polycephalum* exhibits properties that can be harnessed to implement systems for generative audio and music. However, the issue of real-time use needed to be addressed to establish how the organism may be useful for sound and music (Waypoint 3).

5

Physarum polycephalum Memristors

5.1 Chapter Overview

This chapter presents the initial investigations into harnessing the memristive characteristics of *P. polycephalum* for CM. These investigations mark the start of the research's pursuit to develop purpose-made musical devices that use *P. polycephalum's* behaviour in as close to real-time as possible (Waypoints 3 and 4).

Firstly, the text presents a set of experiments to confirm that the protoplasmic tubes of *P. polycephalum* show I-V profiles that are consistent with that of a memristor. Then, the chapter presents a study that investigates how the memristive qualities of the organism may be used to generate musical responses to seed material. Following on, the system and artefact *BioComputer Music* is presented, which is a piece of music composed for live performance. The structure of this chapter is as follows:

- 5.2 - Introduction
- 5.3 - *Physarum polycephalum*-based Memristors
- 5.4 - Confirming the Memristive Properties of *Physarum polycephalum*
- 5.5 - An Approach to Processing Music with *Physarum polycephalum-based* Memristors
- 5.6 - *BioComputer Music*: Out of the Laboratory and into the Real World
- 5.7 - Conclusions
- 5.8 - Chapter Summary

5.2 Introduction

The initial experiments presented in Section 4.3 produced encouraging results and allowed me to begin addressing the research questions. However, each of the three experiments highlighted the challenges related to harnessing living biological material within creative technology. From the results, it was clear that the major obstacle to overcome is the organism's speed: bio-electrical oscillations are slow, as is the organism's migration. Thus, studying devices that harness oscillatory behaviour and unfolding network topologies is unlikely to produce practical CM devices. To fully address **RQ2** and **RQ3**, the research needs to progress past the sonification and musification of behavioural data by looking to develop systems where musical data is processed in some capacity by *P. polycephalum* in as close to real-time as possible. Moreover, the systems presented in the previous chapter maintained a clear divide between the biological substrate and the music: the data gathering process was independent of the CM process. In part, this was due to the approach of re-purposing established Physarum Machines and not developing purpose-made musical devices. It is also unlikely that continuing this approach would yield positive answers to **RQ3**.

Research in this chapter had three key aims that went towards addressing **RQ1**, **RQ2**, and **RQ3**. The first aim was to establish feasible methods of implementing CM systems that were not bound to time-consuming behaviour recording processes. Achieving this lessened the division between the biological substrate and the musical processes as it was possible to move towards implementing more instantaneous control over the organism. By accomplishing this aim, the research journey arrives at Waypoint 3. Aim two was to investigate the type of CM system that could be developed to best take advantage of the speedier methods. Finally, the third aim was to develop a proof-of-concept piece of music technology that could be deployed in a real-world CM application (Waypoint 4). This final aim led to a collaboration with contemporary composer Eduardo Miranda who used the system to perform a piece of music at a public concert. The purpose of this collaboration was twofold. Firstly, by developing technology for an independent composer, an understanding could be built of the challenges related to implementing systems with *P. polycephalum* for the CM community. Furthermore, it prioritised addressing practical usability issues. Secondly, by having a demonstration of the technology as the centre piece of a nationally publicised festival, it was possible to gauge how well the work disseminated across the CM community. It is important to note that there was a clear division of labour during the collaboration. I was wholly responsible for the technology while Eduardo was responsible for the scored composition.

5.3 *Physarum polycephalum*-based Memristors

Today's computers are built using the three two-terminal fundamental passive circuit elements: capacitor, resistor, and inductor. Passive elements are only capable of dissipating or storing energy, not generating it. These elements were established in the 18th and 19th century and are linked through Maxwell's equations. We define each of these three circuit components in terms of their relationship between two of the four circuit variables namely current (I), voltage (V), charge (Q), and flux-linkage (φ). The charge is the time integral of the current and Faraday's law defines the voltage as the time integral of the flux. Thus, a capacitor is defined by a relationship between voltage and charge, a resistor is defined by a relationship between voltage and current, and the inductor is defined by a relationship between flux and current. For well over a century, these elements were a cornerstone of electronics. However, these elements only represent three of the possible four relationship pairs between the circuit variables, leaving flux-linkage and charge unlinked. In 1971, Leon Chua published an article where he postulated that there was a missing fourth element that linked the remaining two variables (Figure 5.1), which he called the memristor (197). Within the paper, he predicted what the memristor's behaviour would be and proved that no combination of the other three elements could duplicate its properties. Thus, the memristor is a fundamental element.

The word memristor is a contraction of 'memory resistor', which describes the element's function: a resistor that remembers its history. Memristors alter their resistance as a function of the previous voltage that has flown through and the length of time that it has been applied. Furthermore, when you stop applying voltage, the memristor retains its most recent resistance state. In contrast to the other three fundamental elements, memristors are intrinsically non-linear. We can observe such non-linearity in its current versus voltage profile, which takes the form of a pinched hysteresis loop when applied with an AC voltage - a Lissajous figure formed by two perpendicular oscillations creating a high and low resistant state. Hysteresis is where the output of a system is dependent on both its current input and history of previous inputs. Chua's paper described the memristor's hysteresis as a figure of 8 where the centre intersection is at both zero voltage and current (Figure 5.2). We can observe the element's memory function in this profile where each voltage has two current readings, one on the ramp

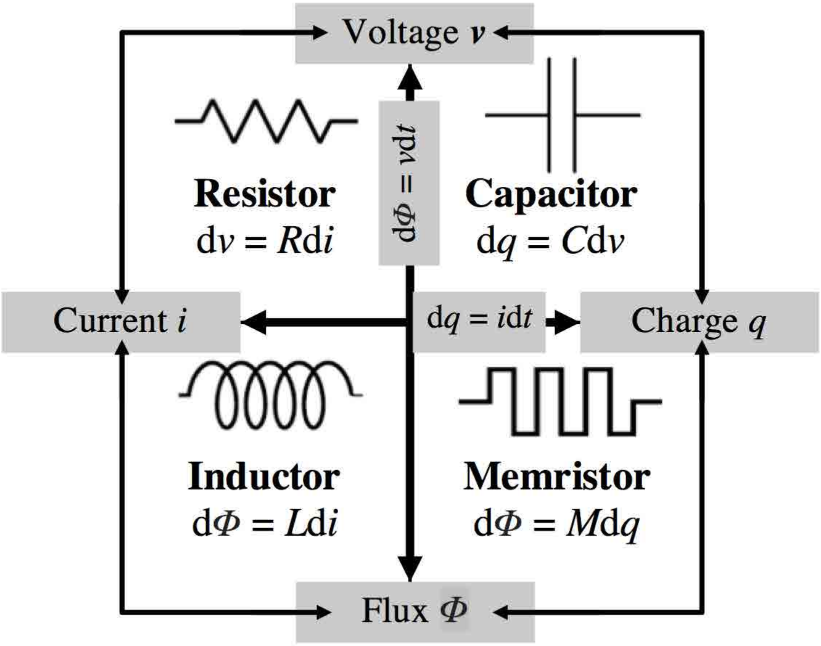


Figure 5.1: The symmetrical relationship between the four fundamental passive circuit elements. This image is based on a figure from (5, p.80).

up to maximum voltage and one on the ramp down. The magnitude of hysteresis lobe size changes as a function of both the frequency of the AC voltage and the memristive system's response time. A good analogy for understanding how a memristor functions is a water pipe whose diameter alters according to the direction the water is flowing through. In one direction, the diameter gets smaller, and, in the other, it gets wider. Furthermore, when the water stops flowing, the pipe's diameter retains its size until the flow continues once more.

We can describe memristance using a state-dependant Ohms law, which is mathematically denoted below:

$$M = R(q) = \frac{d\varphi(q)}{dq} \tag{5.1}$$

where q is charge and φ is flux-linkage.

Although Chua published his paper in 1971, his memristor concept did not gain much interest from the scientific community for decades. In 2008, however, a research group based at Hewlett-Packard (HP) managed to construct a component whose be-

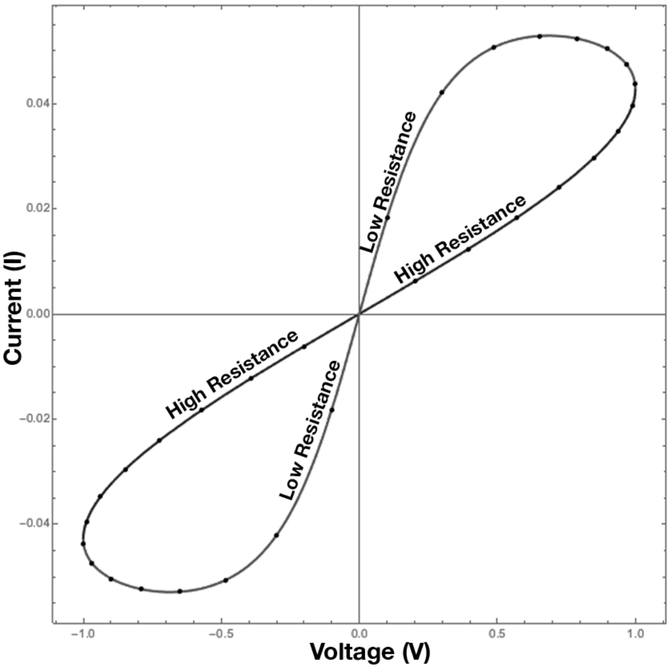


Figure 5.2: Example of hysteresis in an ideal memristor (arbitrary values used).

haviour was that of a memristor's (5). Since, computer scientists and engineers have developed a keen interest in experimenting with the memristor, which is due, in major part, to properties that have promise to revolutionise the way our computers work. For example, investigators have credited memristors as being the first to combine processing and memory abilities in a single component (198). Moreover, the component's behaviour has a likening to the way that synapses in the brain function (199): synapses are structures that allow neurons to communicate via chemical or electrical signals. Thus, today we have perspectives of memristors providing the bases for new 'brain-like' technologies (174). Although interest in memristors is thriving, there is accessibility issues that limit the extent of which people can experiment with them. Currently, the component is not yet commercially available and is difficult for researchers to fabricate in the laboratory (200). Fortunately, a selection of researchers have looked past conventional approaches to developing memristors and have discovered that a variety of natural systems exhibit memristive properties. For example, Aloe vera plants (201), human skin (202), and, most relevantly, the protoplasmic tube of *P. polycephalum*.

P. polycephalum's memristive investigations began in 2008 when Saigusa et al.

(203) ran experiments which demonstrated that the plasmodium can anticipate periodic events. Shortly after, Pershin et al. (70) published a paper that described the plasmodium's adaptive learning behaviour in terms of a memristive model. Building on these research developments, Gale et al. (200) demonstrated in laboratory experiments that the protoplasmic tube of *P. polycephalum* showed I-V profiles consistent with memristive systems. Gale's work provided the basis for other researchers to develop memristor and memristor-transistor prototypes (204, 205).

The discovery that *P. polycephalum* can act as a memristor is providing researchers with an opportunity to begin developing everyday information processing systems using biological components. In regards to music, the memristor's abilities could enrich our approach to developing creative computer music tools. In particular, the component's ability to alter its internal state according to its history and current input may prove to be a productive approach to implementing systems to aid composition and for real-time improvisation. Research in this chapter explores the feasibility of engineering biological processing systems using *P. polycephalum*-based memristors for music. Here, the memristor's ability to alter its resistance as a function of the input voltage and history of voltages is explored as a mechanism for generating responses to seed music.

5.4 Confirming the Memristive Properties of *Physarum polycephalum*

At the time of this research, there was only one paper investigating memristance in *P. polycephalum* (200). Thus, before investigating how these organic processing components may be used for CM, it was first necessary to confirm the initial findings. Here, a set of experiments were conducted to demonstrate that the protoplasmic tubes, henceforth known as components, show current versus voltage profiles consistent with memristive systems. Furthermore, experiments were conducted on retired protoplasmic tubes —those which have dried up —to review if memristance is dependent on a functioning organism. To the best of published knowledge at the time of investigation, this research was the first to study *P. polycephalum*-based memristors for a real-world application. Therefore, it was also necessary to expand on the original findings to gain a greater insight into the nature of these components. Here, experiments were run to review repeatability and sustainability. Such aspects were important to address in order to understand how much control a practitioner may have over systems that encompass these *P. polycephalum*-based memristors. Furthermore, the experiments indicated how long the organism could function as an electrical component under constant use.

5.4.1 Methods

To confirm Gale et al.'s findings (200), the same experimental setup was used. This setup is similar to those outlined in the previous chapter. Two electrodes were spaced at a distance of $\approx$10mm within 60mm Petri dishes. Each electrode consisted of a circle ($\approx$20mm in diameter) of tinned copper wire (16 stands at 0.2mm) filled with a 2% non-nutrient agar ($\approx$2ml). To grow the components, a colonised oat flake was positioned on one of the electrodes and a fresh oat flake on the other. This arrangement caused the plasmodium to propagate along a chemical gradient to the fresh oat, resulting in a protoplasmic tube linking the two electrodes (Figure 5.3). All Petri dishes were stored in a plastic container with a damp cloth fixed to the lid, which kept humidity high to promote growth. For these experiments, 20 samples were created using these methods.

Electrical measurements were made using the Keithley 230 Programmable Voltage Source and the Keithley 617 Programmable Electrometer. Custom software controlled

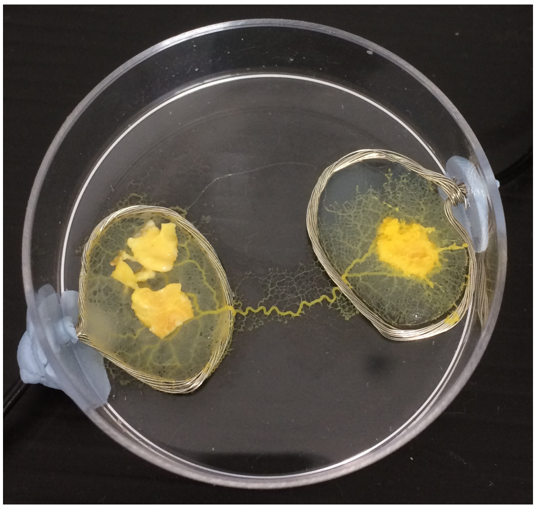


Figure 5.3: A photograph of the experimental setup. Shown is two electrodes comprised of a circle of wire filled with non-nutrient agar, linked by a protoplasmic tube.

each of these devices using two Prologix GPIB USB controllers. The software took I-V measurements by instructing the 230 Keithley to source voltage while using the Keithley 617 to measure the component's instantaneous response. Measurements were taken under a discretised sinusoid A.C. voltage waveform of 160 steps. These are calculated by the software within a user-specified voltage range, which are listed below. Subsequent voltage steps are sequentially communicated to the Keithley voltage source at the appropriate time-steps.

As memristance is a voltage and frequency effect, the 20 samples were divided into 4 batches of 5 that were each tested under different ranges. Here, samples in batch 1 were tested under a voltage range of ± 50mV and 100mV; batch 2 samples under ranges ± 200mV and 250mV. Batch 3 samples were tested under ± 500mV and 600mV, and, finally, batch 4 samples were tested under ± 1V and 1.5V. Batches 1 and 2's voltage ranges are from the original *P. polycephalum* memristor testing. At these magnitudes, the internal current produced by the organism's intracellular movement was found to oppose or add to the driven current, which resulted in asymmetrical I-V curves. For this reason, it was decided to explore using higher voltage ranges that were likely to result in current readings of a higher magnitude, limiting the impact of the organism's internal current source on hysteresis. Instantaneous resistance readings were made with each batch under measurement and voltage time-steps of Δt=0.5, 1, 2

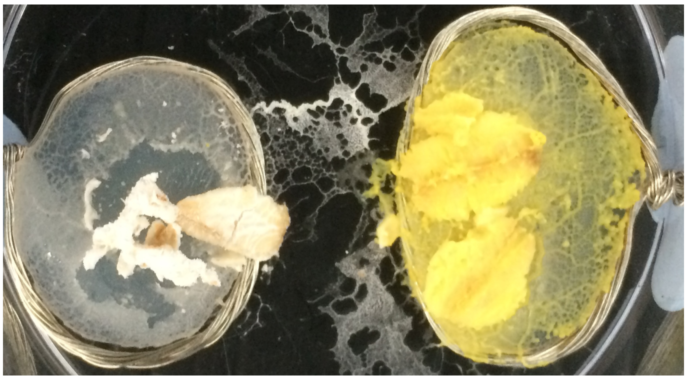


Figure 5.4: A photograph of a retired protoplasmic tube, which is distinguishable due to the lightening and hardening of the outside of the tube.

and 2.5 seconds. As the organism has an innate reaction to light, all experiments were performed in the dark.

After initial testing, 5 of the 20 samples were left until the organism retired the linking protoplasmic tube. These samples were then retested to ascertain whether memristance was dependent on living biological material. Retired protoplasmic tubes are distinguishable by a lightening and hardening of the outside of the tube (Figure 5.4).

5.4.2 Results

After ≈30 hours, all samples produced the required protoplasmic tube. Each of these tubes varied heavily morphologically, which is likely a result of the organism spanning other areas of the environment before discovering the food on the opposite electrode. Over time, several samples optimised their connection between the two electrodes by shortening their tube length. All 20 samples were electronically connected and, as such, each had their I-V curves measured. After testing each sample, the 5 arbitrary chosen control samples were left to retire the linking protoplasmic tube, which took approximately a further 24 hours in a low humidity environment.

5.4.2.1 Memristive Curves

Measurements on the 5 samples in batch 1 produced 5 and 6 pinched I-V curves using voltage ranges ± 50mV and 100mV, respectively. At the lower two time-steps, only 1 sample produced a pinched curve, which was using a ±50mV range and $\Delta t = 1s$ time-step. Tests with a $\Delta t = 2s$ produced 1 pinched curve at ±50mV and 3 at ±100mV. Finally, 3 samples at each voltage range produced pinched curves at $\Delta t = 2.5s$.

Batch 2's voltage ranges were the ones shown to work best in the original *P. polycephalum* investigation. Results from these experiments, however, were in contrast to the original findings. Here, a total of 9 pinched I-V curves were measured across the 4 different time-steps. Under the lower two, 1 sample produced a pinched curve, which was using a voltage range of ±200mV and measurement rate of $\Delta t = 0.5s$. At $\Delta t = 2s$, 3 samples under ±250mV produced pinched curves while only open curves were recorded at ±200mV. Lastly, 5 samples using $\Delta t = 2.5s$ recorded pinched curves, 3 of these were with a voltage range of ±200mV and the remaining 2, ±250mV.

Test results under the higher voltage ranges of batch 3 (± 500mV and 600mV) were more successful than previous batches. A total of 15 pinched curves were measured across both voltage ranges spanning the 4 different time-steps. $\Delta t = 0.5s$ produced 1 pinched curve using the ±600mV range. 2 samples using ±600mV and a $\Delta t = 1s$ demonstrated pinched curves. At this point in the testing, there was increased success using $\Delta t = 2s$, with 3 and 5 samples producing pinched curves under ± 500mV and 600mV, respectively. Tests using $\Delta t = 2.5s$ produced 4 pinched curves, equally split across both voltage ranges.

Finally, testing under the higher voltage ranges of batch 4 resulted in a total of 21 pinched curves. 3 pinched curves were measured at $\Delta t = 0.5s$, 1 at ±1V and 2 at ±1.5V. At the $\Delta t = 1s$ time-step, only 2 samples under ±1.5V recorded pinched curves. All samples tested under both voltage ranges demonstrated pinched curves at $\Delta t = 2s$. Lastly, 6 pinched curves were measured under $\Delta t = 2.5s$, equally split across the two voltage ranges. Examples of pinched I-V profiles are shown in Figure 5.5 while samples of measured open curves are displayed in Figure 5.6.

Of the 5 control samples, 0 presented memristive curves. Moreover, there was no discernible increase in resistance. These results are indicative that observable memristive characteristics are a result of functioning biological material. I-V plots of three control samples are displayed in Figure 5.7.

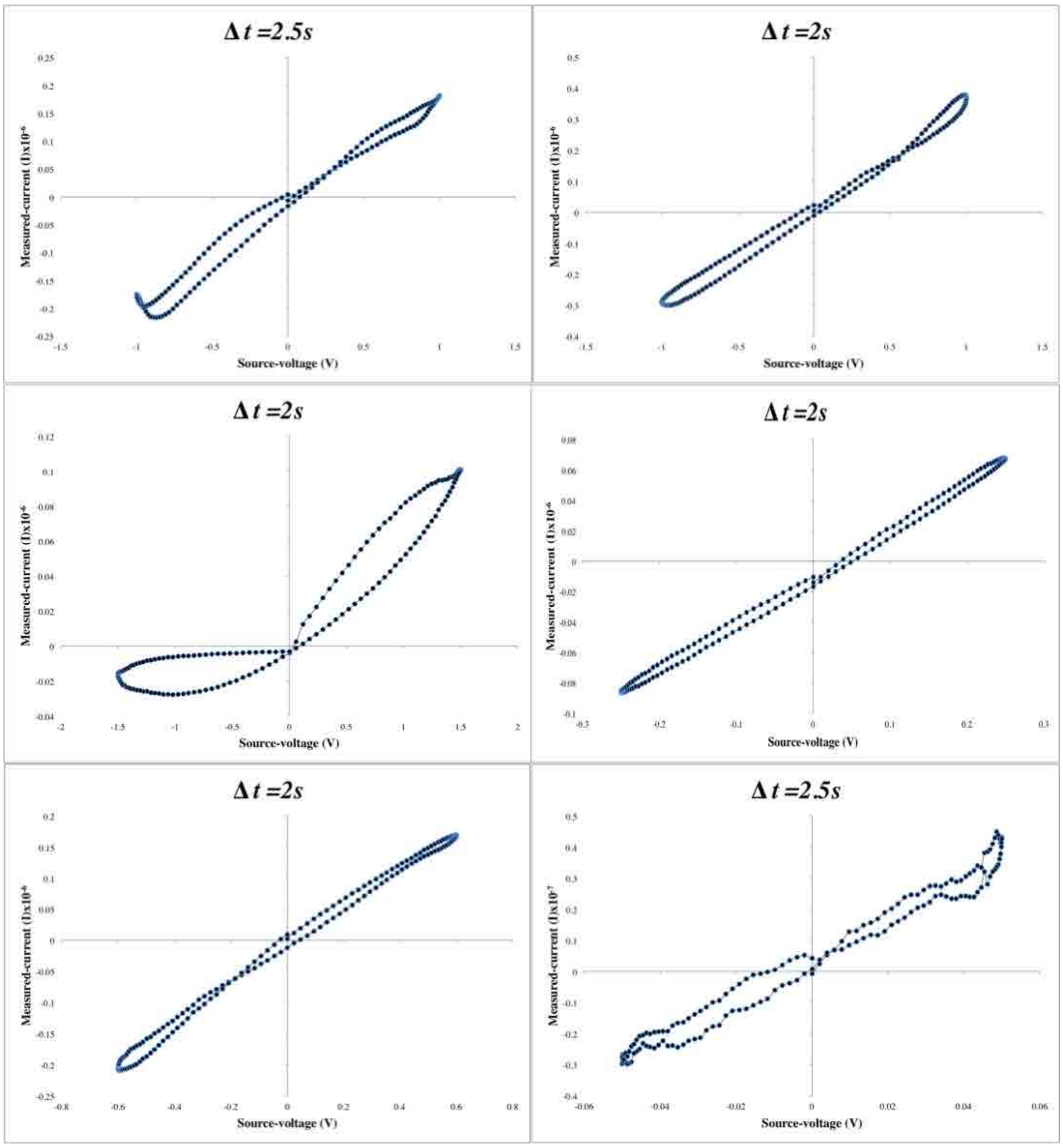


Figure 5.5: 6 examples of pinched I-V curves recorded during testing.

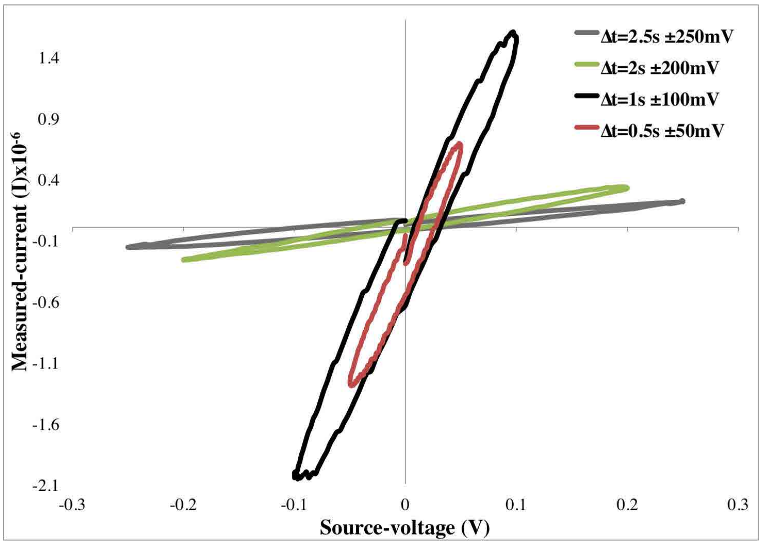


Figure 5.6: Four examples of open I-V curves recorded during testing.

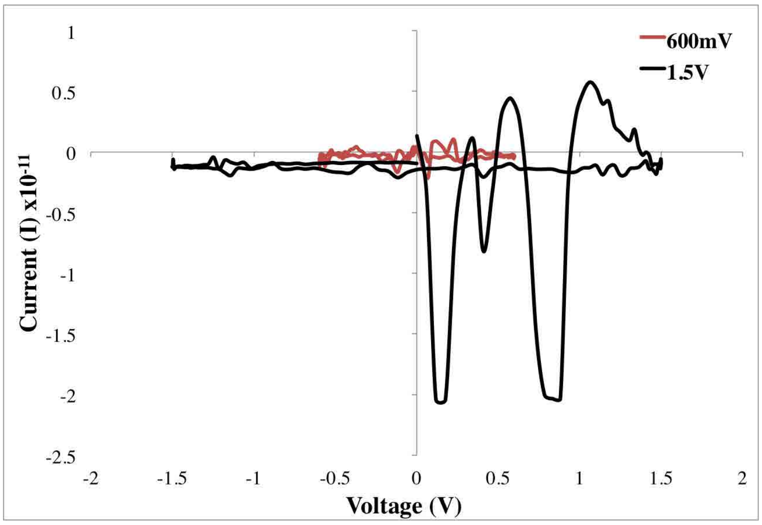


Figure 5.7: I-V tests run on retired protoplasmic tubes —like those shown in Figure 5.4 —depicting no memristive or increasing resistance effects.

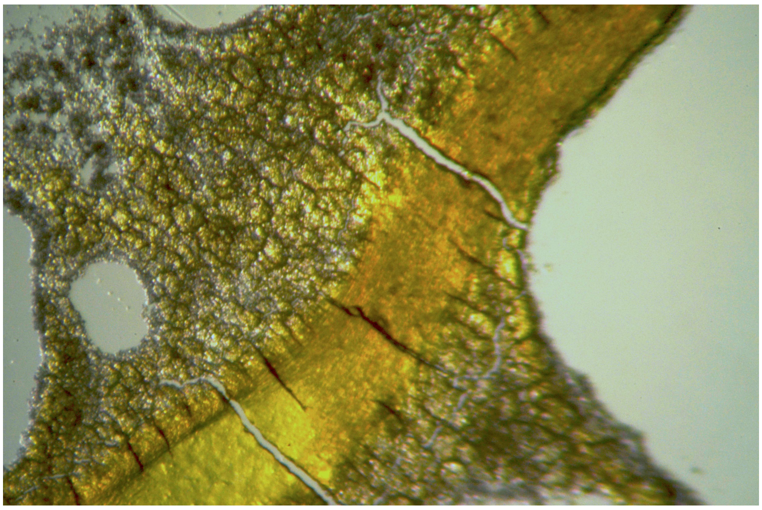


Figure 5.8: A photograph under a microscope of a protoplasmic tube that has dried out and split after successive applications of voltage.

5.4.2.2 Frequency Effect and Repeatability

From these results it is clear that a frequency of $\Delta t = 2s$ or higher worked best for producing pinched curves. This is likely due to the time the organism takes to respond to a change in voltage across its terminals. The shape of each sample's I-V curves measured at different time-steps and voltage ranges were morphologically similar. However, measurements under the higher time-step of $\Delta t = 2.5s$ often had sporadic morphologies, an example of which is shown in the bottom right I-V profile in Figure 5.5. Such morphology may be a result of the longer time-step allowing the organism's cytoplasmic streaming to begin the locomotion of ions contained in the cytoplasm.

In regards to repeatability, it was clear the testing process was not conducive to maintaining a healthy and functioning protoplasmic tube: successive ($\approx$2 hours worth) applications of voltage caused the protoplasmic tube to dry out (Figure 5.8), which causes the organism to begin foraging elsewhere. In the cases of lengthy application using the higher magnitude voltages of batch 3 and 4, in several instances the organism would not attempt to forage elsewhere but would instead enter its dormant sclerotium phase. It was found that these occurrences could be delayed by fixing a damp cloth to the lid of the Petri dishes to increase humidity.

In line with original *P. polycephalum* memristor findings, results showed that re-

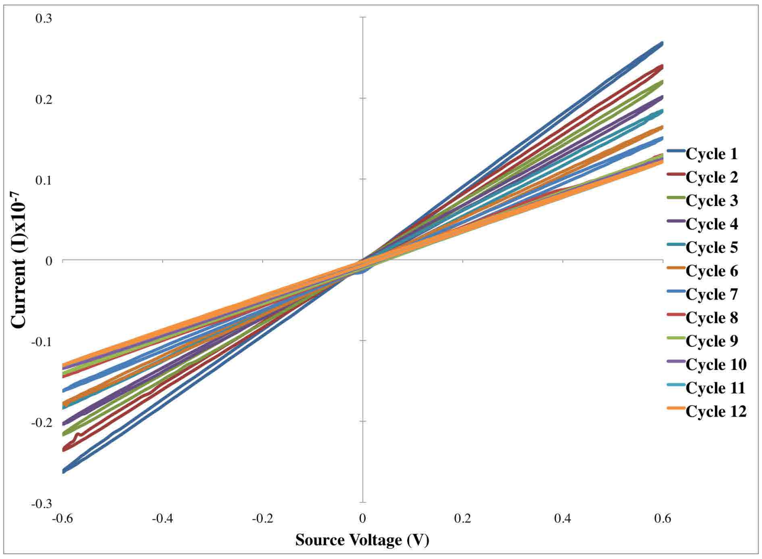


Figure 5.9: 12 sequential I-V profiles showing that the protoplasmic tube's resistance increases under successive applications of voltage before plateauing.

peated application of voltage caused the protoplasmic tube's resistance to increase. To further examine this increase in resistance effect, an extra 5 samples were setup and measured under 12 successive wave cycles at ±600mV using a time-step of $\Delta t = 2s$. The I-V plots in Figure 5.9 show that the protoplasmic tube's resistance progressively increases for the first 7 cycles and then plateaus for the remaining 5. Each of the 5 samples that were tested exhibited the same increase and plateauing resistance behaviour. Plateauing consistently occurred around half way through the tests. During this testing it was also noted that hysteresis lobe size decreased over time, leading to a more linear resistance profile.

Under periodic testing —an hour's worth every 24 hours —, each sample had a life span of $\approx$3 days. This could be extended by $\approx$2 days by placing extra oats on both electrodes and maintaining adequate humidity and temperature for the samples. Under constant testing with a ±1.5V range in a high humidity and cool environment, samples continued to exhibit memristive curves for $\approx$2 hours.

5.4.3 Discussions

Results show that the protoplasmic tube of *P. polycephalum*, under the appropriate time-step and voltage range, exhibits I-V curves that are consistent with memristive systems. By this I mean the measured hysteresis loops are pinched; a time-step of $\Delta t = 2s$ and voltage range in excess of ±500mV worked best. However, although curves measured on the same sample were morphologically similar, hysteresis varies heavily from sample-to-sample. Such variation includes the location of pinch points, the magnitude of both positive and negative lobes, and the symmetry between measurements in the negative and positive voltage domains.

The pinched I-V curves measured during the experiments are not the footprint of an ‘ideal’ memristor. One of the characteristics that classify a memristor as ‘ideal’ is that it does not store energy (206); a memristor is a passive circuit component. Thus, the hysteresis pinch points should be at zero voltage and current. In these results, the location of pinch points vary heavily, which results in an asymmetry between positive and negative hysteresis lobes. An example is shown in Figure 5.10. It is likely that such variation is due to the organism producing an internal current source, which, dependent on the direction of flow, will oppose or add to driven current. This current source is potentially a result of the organism’s innate shuttle streaming behaviour causing the shift of ions contained in the cytoplasm. Furthermore, it is likely that several of the biological components which make up the plasmodium, and their configurations, are affecting electrical observations. Therefore, it is plausible that the organism is not only functioning as a memristor but as a complex circuit comprising a number of different electrical components with dynamic parameters. To date, researchers have demonstrated that the organism can function as an electronic oscillator (124) and low-pass filter (207), to cite but two. Moreover, it has been demonstrated that the plasmodium’s electrical properties can be modulated by the application of nanoparticles and nanostructures (208). Here, it was shown that nanotube-treated plasmodia had a higher capacitance and lower electrical resistance.

To support the hypothesis that shuttle streaming may have affected the I-V measurements, the background current of a protoplasmic tube was measured every 500-milliseconds for 2000 seconds. Results were also studied for any oscillations that may

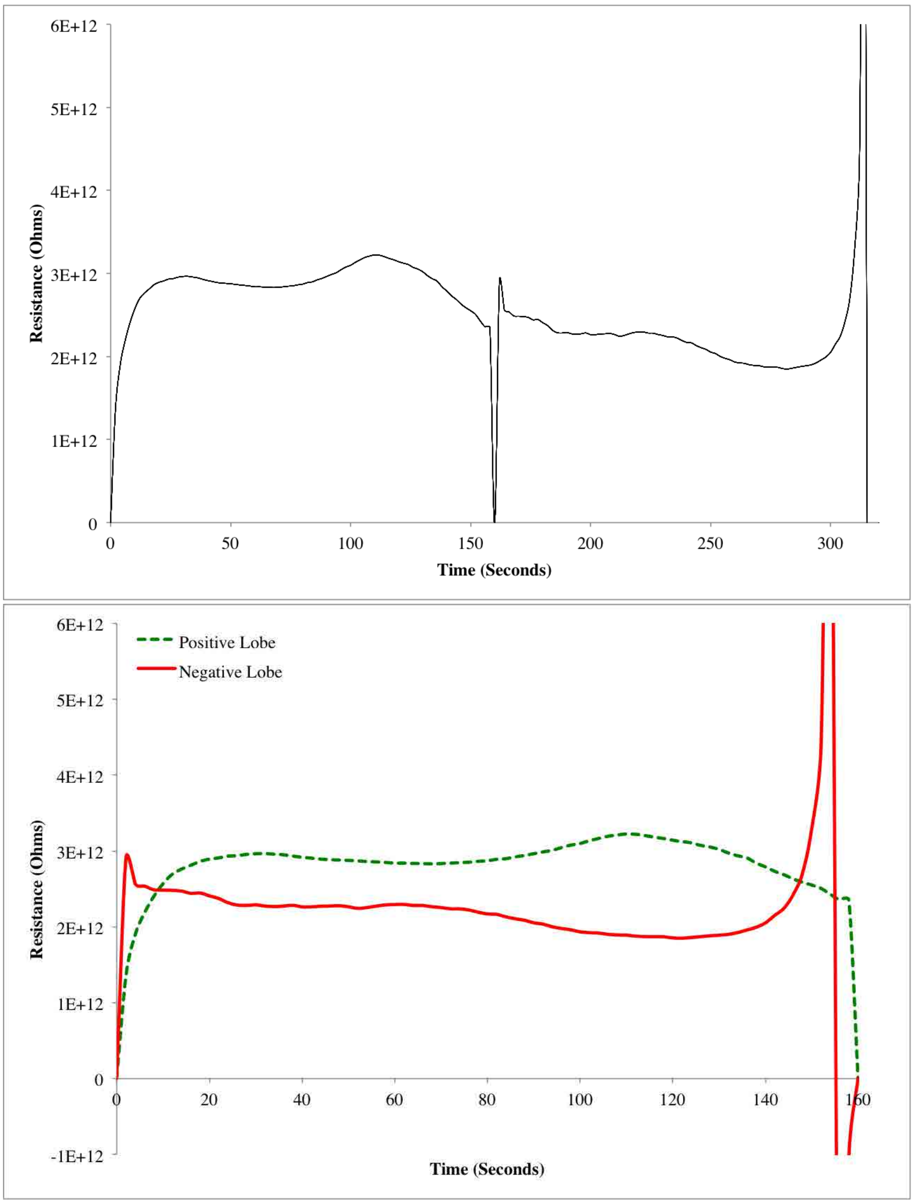


Figure 5.10: Resistance-time plots. The top graph shows resistance over a complete wave period while the bottom shows the difference in resistance between the positive and negative lobes of a pinched I-V curve. To be classified as an ‘ideal’ memristor, there should be no difference between these two lines.

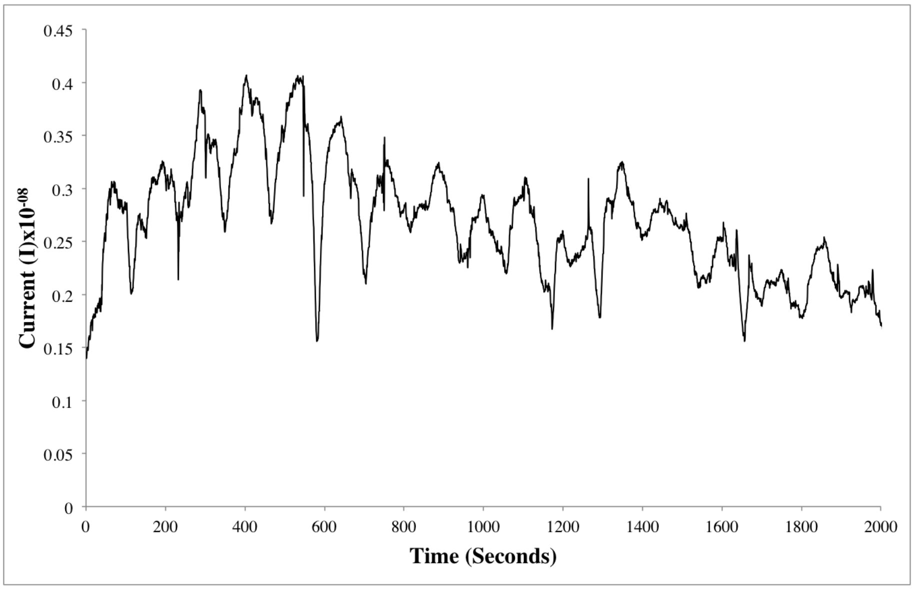


Figure 5.11: Background current-time plots of a protoplasmic tube showing visible oscillatory behaviour.

indicate that the background current is a result of the periodic back-and-forth movement of cytoplasm. The time-current plot depicted in Figure 5.11 confirms that the protoplasmic tube's background current is indeed of a magnitude that will impact current measurements under the voltage ranges used to make I-V measurements. This internal current source will have less impact under incremental voltage ranges; for example, batch 4 produced I-V curves more reminiscent of an 'ideal' memristor's profile. Moreover, the plot shows visible oscillations which are indicative that the current is generated by the organism's streaming behaviour. It is possible that this phenomenon could give rise to memristive effects. However, as confirmation that this behaviour does not give rise to the measured I-V curves, the average period over the 2000 seconds was $\approx$85.14 seconds, which is just over a quarter of the 320-second voltage waveform period when using the best time-step of $\Delta t = 2s$. (200) provides a theoretical analysis of the protoplasmic tube as an active memristor, which looks to begin understanding the asymmetrical nature of *P. polycephalum* I-V curves.

Comparing these results against those of the original *P. polycephalum* memristor experiments, there is one inconsistency. In the original results the team had 100% success rate at ±250mV, however, in these results, the presence of pinched curves was fairly inconsistent below ±500mV. All other findings were consistent: the best time-step was $\Delta t = 2s$, no memristive properties observed in retired protoplasmic tubes, successive applications caused an increase in overall resistance, and I-V profiles presented with asymmetry between positive and negative lobes.

5.5 An Approach to Processing Music with *Physarum polycephalum*-based Memristors

From an electrical engineering perspective, the non-standard nature of *P. polycephalum*-based memristors would likely be detrimental to most applications. However, in regards music, such variation can be desirable and even sought after: composers have been known to use a wide span of different processes (e.g. stochastic) to evolve their compositions. As such, consistency in hysteresis was not a pressing issues at this stage of research. On the contrary, this non-standard nature highlighted a potential benefit of harnessing biologically-based memristors over silicon versions. Here, as the components are ever-changing living entities that respond to their immediate environment, it is likely that aspects of hysteresis can be controlled via methods of stimulation. If it is possible to control hysteresis, musicians may be able to dynamically interact with organic-based memristor technology. Thus, component response variation was studied as a stylistic trait of using *P. polycephalum*.

This section presents an initial investigation into harnessing the memristive characteristics of *P. polycephalum*, specifically its non-linear conductance profile, to generate musical responses to seed material. To begin the investigation, a basic mapping approach was developed that enabled the encoding and decoding of musical information to and from the memristors. Initially, it was decided to explore generating responses to pitch; at this stage, duration, loudness, or rhythmic structure were not considered. By limiting the first attempt to one parameter, it was possible to gain a clear appreciation of how to best approach harnessing a memristor's input-output space for music. Moreover, it was a useful knowledge building process to experiment with the basics of simple note transformation before building a complex multimodal system. As such, all this section's examples are displayed with notes that have been assigned the same arbitrary duration, loudness, and rhythm.

P. polycephalum-based memristors are analogue components whose input parameters include voltage and frequency, and output parameters include current and measurement offset. In the first instance, the investigation was in pursuit of finding the most transparent and straightforward approach to encoding musical information for inputting into a memristor and transcribing its subsequent output to generate a reply.

Figure 5.12: A flow diagram of the basic mapping approach for generating pitches using a memristor.

As such, one of each of the memristor's input and output parameters were used to create a direct transcription approach. Here, it was decided to encode pitch information at note level using discrete voltages and generate a response by transcribing subsequent current readings into notes. A flow diagram of this approach is displayed in Figure 5.12.

5.5.1 A Basic Mapping System for Generating Pitches

To implement the described approach, software was developed that works as a translator between incoming music and *P. polycephalum* component. The software first requires the user to input a vocabulary of pitches for the system to use. There are two options here: either a custom vocabulary can be input or the software can be told to only generate responses using notes that have previously been input. This information allows the software to assign a unique voltage value to each note in the vocabulary. The transcription process uses a voltage range of 0-1V, which was selected in accordance with the findings presented in the previous section: higher voltages produced more pinched curves. Furthermore, previous findings also highlighted that successive applications of voltage increased the components overall resistance. Thus, to take this phenomenon into account, 0V and 1V are reserved for component calibration purposes.

The software uses a logical note-to-voltage transcription process where voltages are assigned to notes in ascending order according to pitch. Table 5.1 demonstrates this process for a vocabulary containing every note in an extract to the introduction of Nimrod, by Edward Elgar, which is depicted in Figure 5.13.

The system was programmed to accept input as MIDI data, either in the form of a live MIDI instrument or a single track MIDI file. As music is played in, the software transcribes each note into its respective voltage value. Then, in batches of 15 notes or 10-second's worth of notes, these voltages are put together to form a discretized waveform with a static time-step of 2-seconds. During this process, note voltages are

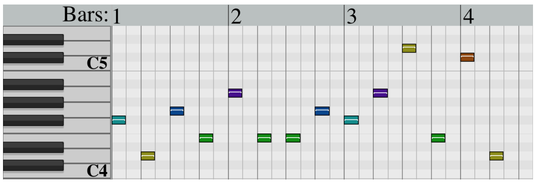


Figure 5.13: An extract of the introduction melody to Nimrod, by Edward Elgar.

Table 5.1: The note-to-voltage transcription process for every note in the melody depicted in Figure 5.13.

Music Note	MIDI #	Voltage
C4	62	125 mV
E4	64	250 mV
F#4	66	375 mV
G4	67	500 mV
A4	69	625 mV
C#5	73	750 mV
D5	74	875 mV

considered absolute values: for example, -0.5V and 0.5V are the same note. To input the notes as an AC waveform, 2 batches create one wave cycle, with batch 1 using the positive voltage domain and batch 2 using the negative. In order to calibrate the current-to-pitch transcription process, the calibration voltages are placed between each batch to create the wave's crest and trough. Figure 5.14 depicts the input waveform for Nimrod (Figure 5.13), using the voltage vocabulary detailed in Table 5.1.

Once the system has enough notes to produce one wave cycle, it instructs a Keithley 230 voltage source to begin applying the waveform to a *P. polycephalum*-based memristor. At each voltage step, and interfacing with a Keithley 617 programmable electrometer, the software takes an instantaneous current measurement. Readings taken at the calibration voltages are then used to map the other measurements into MIDI notes by defining a minimum and maximum current value. This procedure is derived from the note-to-voltage transcription stage: higher current measurements result in higher pitched notes. The graph pictured in Figure 5.15 is an overview of the input-to-output mapping procedure for Nimrod. Here, the dotted line is the input voltage sequence while the black line is the memristor's response. The shaded boxes portray seven discrete magnitudes of current that the readings are quantised into. Each of these corresponds to one of the seven notes in the system's vocabulary.

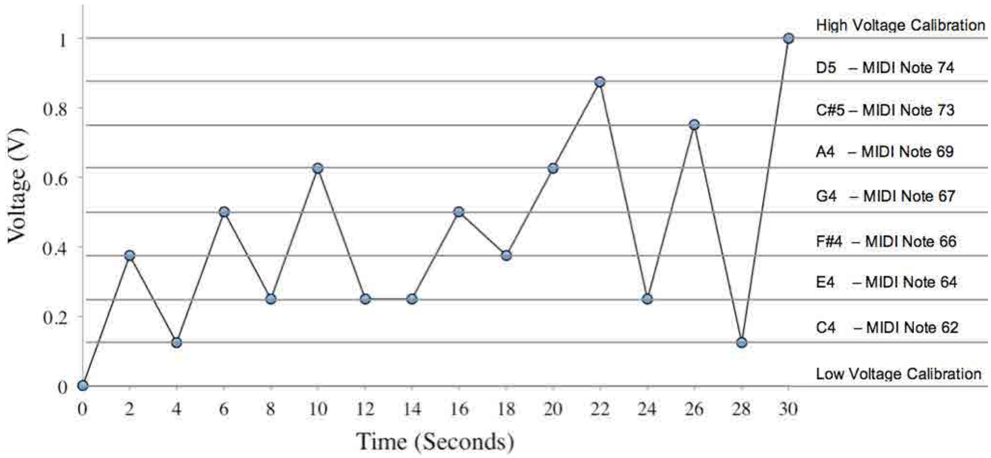


Figure 5.14: The input voltage waveform for the introduction melody to Nimrod (Figure 5.13).

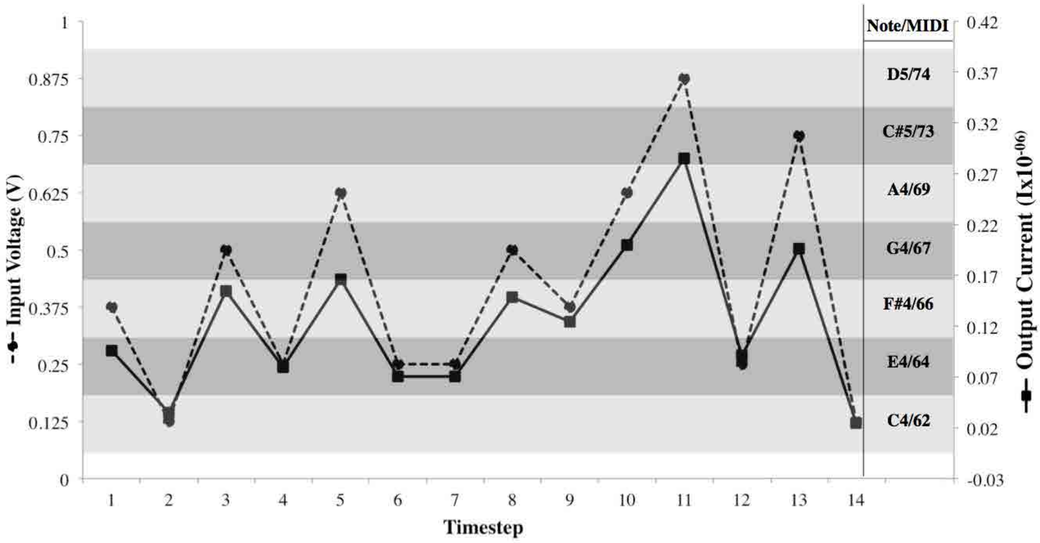
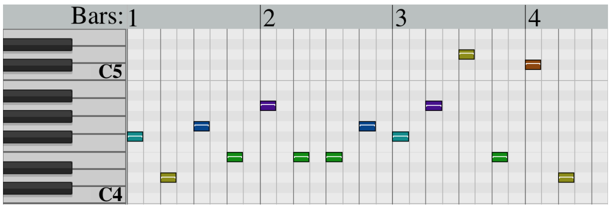
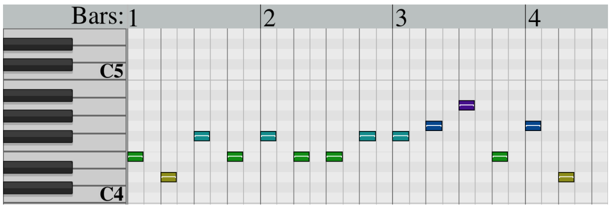


Figure 5.15: An overview of the input-to-output mapping procedure exemplified using the extract to Nimrod in Figure 5.13.



(**a**) Nimrod Input.



(**b**) Nimrod Output.

Figure 5.16: An example of a memristor's response to Nimrod, by Edward Elgar.

5.5.2 Results

An analysis of the system's response to Nimrod (Figure 5.16) is presented in Table 5.2 where the directional movement between successive notes within the system's vocabulary was studied. This analysis shows a reduced movement between notes in the response sequence when compared against the input. The absolute average of the movement between notes is 1.3 for the response, which is half of the input's average at 2.6. This reduced movement is likely down to two reasons. Firstly, memristors need time to respond to a change in voltage. The higher the change in voltage, the longer the memristor needs to reach a sustained level of resistance. Secondly, a *P. polycephalum*-based memristor is in a low resistant state when the voltage is increasing, and a high resistant state when the voltage is decreasing. In the case of Nimrod, for example, where MIDI note 64 follows 74, the voltage change is -625mV, which causes a higher resistance and larger voltage change than when note 67 follows 64 (+375mV). Referring to Table 5.2, the distance between sequential notes in the input and output melody movement columns supports this hypothesis. Here, the input's highest movement is -5, whereas the output's largest movement is -3.

Input			Output			
MIDI Note	Note #	Melody Movement	MIDI Note	Note #	Melody Movement	Input-Output Transformation
66	3	-	64	2	-	-1
62	1	-2	62	1	-1	0
67	4	3	66	3	2	-1
64	2	-2	64	2	-1	0
69	5	3	66	3	1	-2
64	2	-3	64	2	-1	0
64	2	0	64	2	0	0
67	4	2	66	3	1	-1
66	3	-1	66	3	0	0
69	5	2	67	4	1	-1
74	7	2	69	5	1	-2
64	2	-5	64	2	-3	0
73	6	4	67	4	2	-2
62	1	-5	62	1	-3	0

Table 5.2: Analysis of the sequence of notes in the system's response to Nimrod (Figure 5.16b).

5.5.2.1 Effects of Asymmetrical Hysteresis

The current *P. polycephalum*-based memristor setup produces asymmetrical I-V hysteresis profiles. To understand the effects of this phenomenon, extra responses were generated to Nimrod and Für Elise, by Beethoven. In both cases, the software could only generate responses with notes that were present in the input.

Figure 5.17 shows a *P .polycephalum* memristor's response to the introduction melody to Nimrod. Here, the input string of notes were sent through the same memristor six times. The software was made to use the positive voltage domain for the first three and the negative domain for the remaining three. By comparing the six voltage responses against the input string in Figure 5.17, it is clear that each of the response's range of note is less dynamic than the input. In these results, it appears that asymmetrical hysteresis has not had an impact on the melody movement of the responses. This is highlighted in Table 5.3, where the mean of the averaged movement across the six responses is the same for both the positive and negative voltage domain.

Regarding repeatability and consistency, morphologically the note distribution of

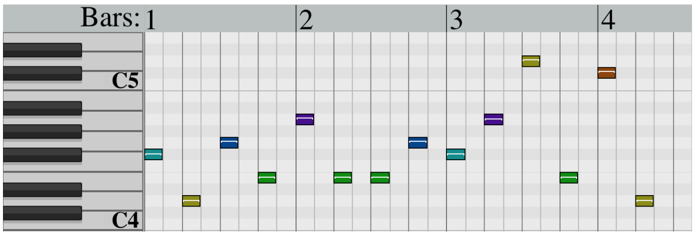
Nimrod	Positive Voltage	Negative Voltage
Input	2.6	2.6
Response 1	1.3	1.4
Response 2	1.6	1.3
Response 3	1.6	1.8
Average Response	1.5	1.5

Table 5.3: Summary of the average melody movements in both the positive and negative voltage responses to Nimrod.

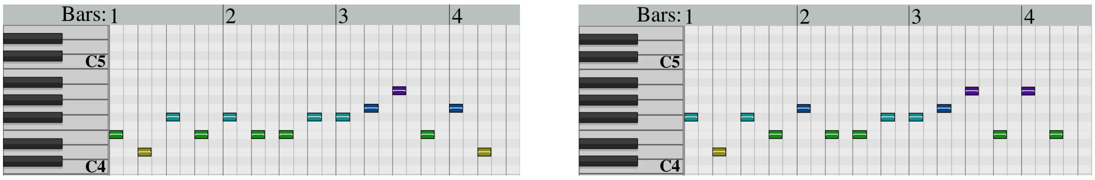
Für Elise	Positive Voltage	Negative Voltage
Input	1.6	1.6
Component 1 Response	0.75	0.88
Component 2 Response	0.75	1.13
Component 3 Response	0.88	0.75

Table 5.4: Summary of the average melody movements in both the positive and negative responses to Für Elise using 3 different *P. polycephalum* components.

each of the responses to Nimrod is similar. However, these results were created using the same component, and, as the earlier tests show, I-V curves produced with the same *P. polycephalum* component are similar in shape. To investigate how responses to the same input may vary from organism-to-organism, the experiment was repeated using three different components and an extract of Beethoven's Für Elise as input. Table 5.4 shows the mean of the averaged movement across each of the 3 component's responses while Figure 5.18 shows an extract of each of the component's responses. These results show a good level of consistency between each component, which may be due to the component calibration process and the small quantity of notes that were available to the system. Even with the limited distribution of input notes, the responses still varied component-to-component.

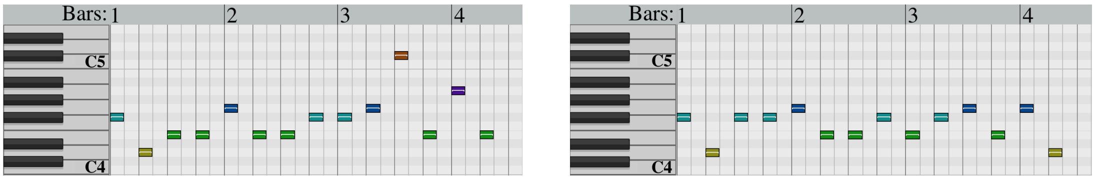


(a) Nimrod input note string.



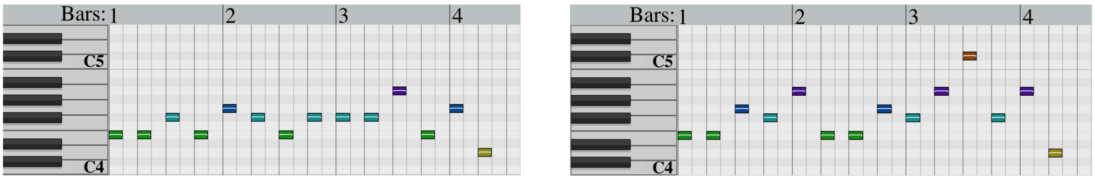
(b) Positive voltage response 1.

(c) Positive voltage response 2.



(d) Positive voltage response 3.

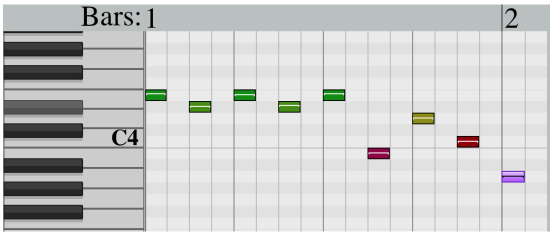
(e) Negative voltage response 1.



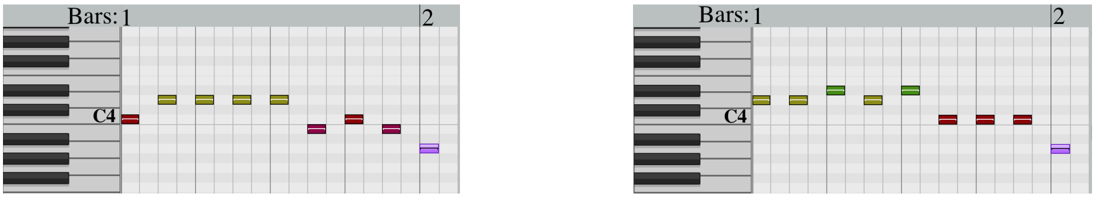
(f) Negative voltage response 2.

(g) Negative voltage response 3.

Figure 5.17: A *P. polycephalum* memristor's responses to the introduction of Nimrod by Edward Elgar. 5.17a shows the input string of notes. 5.17b, 5.17c and 5.17d are 3 successive responses to the input string, using the positive voltage domain. Similarly, 5.17e, 5.17f and 5.17g are 3 responses but in the negative voltage domain.

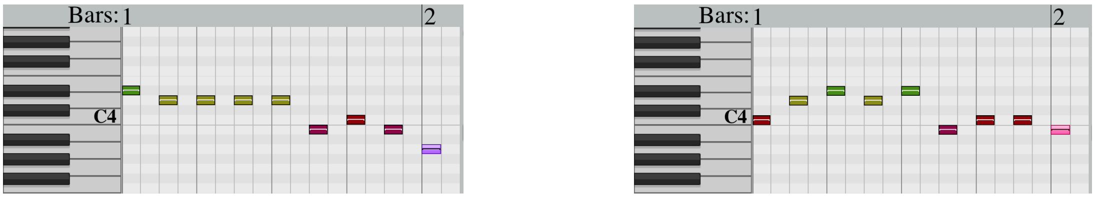


(a) Für Elise Input Note String



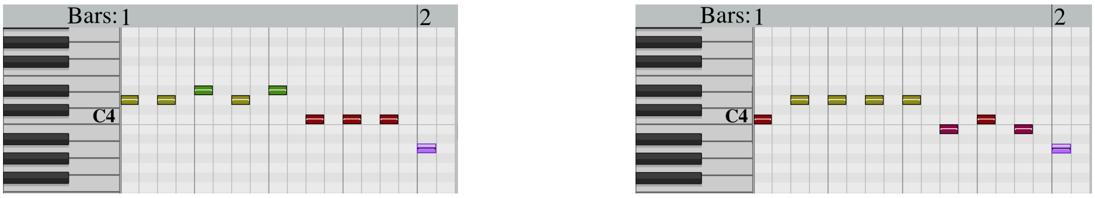
(b) Component 1 positive response.

(c) Component 1 negative response.



(d) Component 2 positive response.

(e) Component 2 negative response.



(f) Component 3 positive response.

(g) Component 3 negative response.

Figure 5.18: Three memristors' responses to the introduction of Für Elise.

5.6 *BioComputer Music*: Out of the Laboratory and into the Real World

This section gives an overview of the music and technology behind the composition *BioComputer Music*. *BioComputer Music* is an innovative duet between a pianist and *P. polycephalum*-based technology, which premièred at the 2015 Peninsula Arts Contemporary Music Festival[1], Plymouth University, UK. The piece was an experiment to begin addressing **RQ2**: is it possible to take *P. polycephalum*-based technology outside the laboratory for application in the real-world? To effectively address this question, the experiment was run in collaboration with a contemporary composer, Eduardo Miranda. Many of Eduardo's previous compositions explore different ways in which computers can aid in musical creativity. The purpose of the collaboration was to develop technology for Eduardo to use in a composition and performance. This approach provided several benefits to the research. Firstly, by developing a system for a third party, it was necessary to address usability issues that could easily be overlooked when developing systems for personal use. Secondly, giving a professional composer access to the technology allowed for the basic mapping approach to be probed in real-world composition and performance. Finally, having music performed with the technology as the centre feature in a well publicised music festival provided means of evaluating how well the work disseminated.

5.6.1 *BioComputer Music* System

The *BioComputer Music* system is an expanded version of the basic mapping system presented in the previous section. As an overview, the system's hardware consisted of ten *P. polycephalum* components, two electrical measurement instruments, USB relay boards, an Apple iPad, a piano, and Andrew McPherson's magnetic resonator piano (MRP) system (209). Each of the ten components corresponded to one of ten performer-switchable software presets that provided means of controlling the parameters of the basic mapping approach. There were several reasons for using this quantity of components. Firstly, as previous experiments highlighted, successive applications

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[1] `http://cmr.soc.plymouth.ac.uk/event2015.html` (Accessed: 13 November 2016)

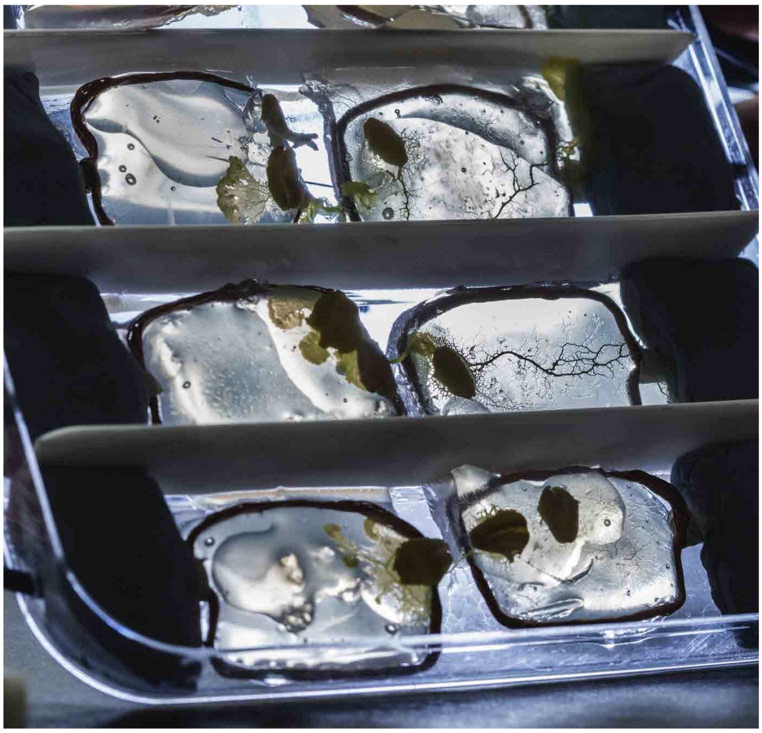


Figure 5.19: Four components grown from the plasmodium of *P. polycephalum* housed in a 120mm square Petri dish.

of voltage have a number of effects on the organism. For example, it encourages migration away from the electrodes and overall resistance to increase. Therefore, the electrical stress can be spread across components, which accommodates longer use. Secondly, as each *P. polycephalum*-based memristor has a unique I-V profile, the composer could experiment with component-to-component response variation. The USB relay boards facilitated automatic switching between memristors when the composer changed preset. Instead of using individual Petri dishes, components were housed in larger 120mm dishes that were divided up into four sections by retrofitting strips of plastic to the base (Figure 5.19).

The piano was furnished with McPherson's MRP system (209), which enabled the *BioComputer Music* system to accompany the performer. The MRP device consists of a set of electromagnets that are capable of exciting the strings of a grand piano. For this piece, there were twenty-four electromagnets positioned above the strings of a mini grand piano (Figure 5.20). These were operated by the *BioComputer Music* software,

Figure 5.20: A photograph of twenty-four electromagnets furnished above the strings of a grand piano.

which requires the user to input what strings the electromagnets are positioned above.

The software side of the system wholly consisted of a bank of ten presets. For each, the performer can define the following parameters: what notes are active out of the available twenty-four, minimum and maximum note duration range, accompaniment speed factor, and electromagnet excitation source. As the basic mapping approach only generates lists of pitches, other computer processes are used to complete the musical accompaniment. Here, note durations are randomly generated using a Gaussian distribution and a second order Markov chain applies rhythmic structure. The Markov chain's output is altered using the speed factor parameter. The electromagnet excitation parameters allow the performer to select which harmonics are used to vibrate the string. Here, up to three sine waves can be synthesised for each magnet. For further control, the magnets can be split into four excitation groups.

As the *BioComputer Music* piece was for one acoustic piano, both the performer and system were playing the same instrument. Such a situation made it difficult to consider using audio-to-note transcription for performer input into the system. Therefore, as the *BioComputer Music* piece was scored beforehand, the software allowed for MIDI files to be input for each preset, which were automatically played into the system upon the preset becoming active. The MIDI data is passed through an algorithm that serves two functions. The first is to transpose the pitches into notes that the performer has made active. For example, if E3 is detected, but only E2 is available, the algorithm will alter the MIDI note to E2. The second function: if a pitch is detected but is not offered and there is not an equivalent available in another octave, the pitch is removed. This algorithm is necessary as it allows the performer to input into the system while playing the full piano range, not just the notes furnished with electromagnets. Once the MIDI file has been played in, the software self-seeds using the system's output. For ease of starting the system and switching between presets at the piano, a user interface was developed for iPad that consisted of on/off controls and ten preset buttons.

As a result of using a voltage step dwell time of 2-seconds, the system can only generate notes at 2-second intervals. For this reason, before playing back any responses, the software was programmed to wait for 30-seconds. Here, notes are stored in a buffer until the lead time is over, at which point the buffer's contents is translated into commands and sent to the electromagnet hardware. If the buffer's contents are exhausted before processing the entire input, the system will calculate the time needed to finish and will fill the time-lapse by repeating previously generated sequences. Conversely, if the system finishes processing the input, it will begin to process the notes it has already generated.

5.6.2 *BioComputer Music* Composition

For the composition of *BioComputer Music*, Miranda was interested in exploring the notion of interactivity between a composer/performer and the *BioComputer* system. He wanted to compose a piece that sounded as if the performer asks questions to *BioComputer*, which in turn answers them. This is a very traditional musical form, which originated from ecclesiastical music where the leader of a ceremony sings a prayer in alternation with a chorus. In addition, Miranda wanted to be surprised by the *BioComputer's* responses, which will vary from performance-to-performance due to component response variation, but within a certain boundary of constraints (presets). Therefore, the piece consisted of materials notated on a musical score for the pianist to play. Once a section is played, the performer selects a preset and the *BioComputer* system plays its response for a given period until the performer turns the preset off and plays another section of the music, and so on. There are also occasions where the pianist plays alongside the *BioComputer* system.

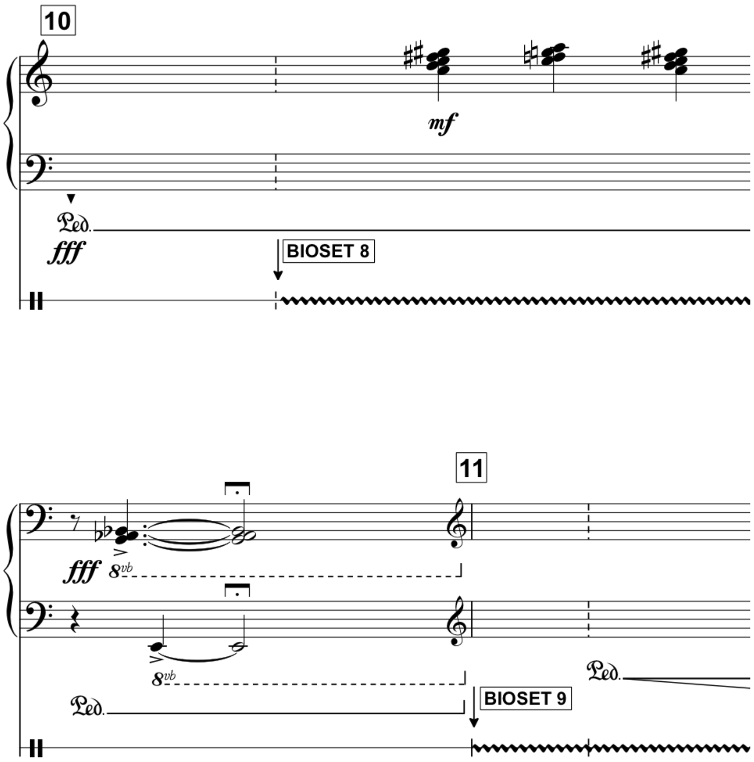


Figure 5.21: An excerpt of the musical score for the composition *BioComputer Music*.

An excerpt of the score is shown in Figure 5.21. In 10, at the top stave, the symbol Bioset 8 is instructing the performer to turn on preset 8. When the system plays its response, the performer accompanies it by playing three chords. At the bottom stave, the passage before 11 is played on the piano before turning on any presets. Preset 9 is then activated when the performer reaches 11.

5.6.3 *BioComputer Music* Discussions

A recording and documentary of the *BioComputer Music* piece can be found on Appendix 1. To the best of published knowledge, *BioComputer Music* is the first composition that harnesses biological circuit components to generate musical responses. *BioComputer Music* is novel both in terms of technology and approaches to creativity. In terms of compositional practice, the *BioComputer* system has enabled Miranda to revisit a few concepts that he has explored in previous compositions, but from a different perspective. One of them is the notion of musical interaction with a non-deterministic machine. Composers used to spend a great deal of time programming digital computers with artificial intelligence to interact with a performer in interesting ways. By interesting ways I mean in ways that are surprising and engaging, but not completely by accident. The *BioComputer Music* system makes this task much easier to achieve: it is a non-linear machine in its own right and displays an intriguing level of intrinsic intelligence, which does not require much programming. Thus, it is highly accessible to the creative practitioner who wants to develop these sorts of musical systems.

In regards to this research, the *BioComputer Music* system marks the beginning of a new avenue. Until now, the research has been focused on using behavioural data that takes several days to gather. The outcomes of these studies are interesting in their own right, but the ultimate goal is to be able to harness *P. polycephalum* for near real-time musical applications. *BioComputer Music* is a large step towards reaching this goal and subsequently answering **RQ2**. Although the system behind the piece is the first implementation, the musical result is both engaging and interesting. Of course, there are several areas that require further development. Foremost, the method of transcribing notes into voltages needs to be improved. Here, it is important to establish more robust and meaningful methods to encode, process, and decode analogue information on the memristors, which take best advantage of the organic component's non-linear conductance profile. Once established, the system can be expanded to generate note durations and rhythmic structure.

By immersing the *BioComputer Music* system into experimental real-time application, it was possible to identify some limitations that need to be addressed going forward. In using the system both for rehearsals and in live concert it was quickly discovered that a lot of time was spent having to fit Petri dishes with the necessary electrical parts, which was tedious and fiddly. Once the plasmodium was inoculated into the prepared Petri dishes, it rarely took under 24 hours for the organism to form the required protoplasmic tube. Thus, the preparation time for an hour's rehearsal/performance spanned several days. This procedure became highly laborious over the process of composing, rehearsing, and performing, which stretched over a duration of four months. Therefore, future research needed to address this issue.

Another considerable constraint was the low level of protection that the setup provided to delicate components. As a result, often components become electrically disconnected when they were moved from the laboratory to where they were required. Thus, memristor implementation procedures needed to be reviewed in order to fully address **RQ2** and **RQ3**. Success here will also provide insights that will go towards addressing **RQ4**

In regards to the system's musical result, as expected there was a high degree of variation component-to-component. This feature was explored in the *BioComputer Music* piece as a stylistic and novel trait of using ever-changing biology entities. However, it became apparent that the ability to produce different results with a degree of predictable control is an important property of musical devices. In several cases, pleasing responses were produced in rehearsals but were not achieved again. Therefore, to widen the usability of using *P. polycephalum*-based memristors for music, responses needed to be standardised.

5.7 Conclusions

This chapter has presented initial investigations into harnessing *P. polycephalum*-based memristors for CM. This area of enquiry was chosen as the memristor is both a processing and a memory component that may provide means of developing genuine biological hardware for near real-time use. Firstly, experiments were conducted that confirmed memristive properties in the protoplasmic tube of *P. polycephalum*. Although the results clearly showed hysteresis and memristive effects in *P. polycephalum*, they were not completely consistent with the original memristor investigation (200). In contrast to their findings, it was found that the presence of pinched curves was very inconsistent below a voltage range of ±500mV.

In Section 5.5, an approach to harnessing the memristor for music was introduced. This approach produced material that was reminiscent of the input, but with variations that were both surprising and engaging. Results from this approach highlighted that inputting musical notes as discrete voltages did not exploit the memristor's input-output space in an appropriate way for music. Assigning voltages to notes in ascending order according to pitch causes higher interval transitions to occur less in the output. This is because the components need more time to react to larger changes in voltage and have a higher resistance when the voltage is decreasing.

Finally, the chapter presented the technology and music behind the piece *BioComputer Music*. *BioComputer Music* was an experimental process that immersed *P. polycephalum*-based memristors into a real-world application. This exercise was a productive exploration as it highlighted some of the constraints of developing CM technology using biological material.

Work from this chapter was well received by the general public and the media. The musical system and *BioComputer Music* composition were reported on via television (210), radio (211), and news agencies (212, 213, 214, 215). This reception goes towards addressing **RQ4** by demonstrating that music is a good vehicle for disseminating UC research.

5.8 Chapter Summary

The research in this chapter has illustrated that *P. polycephalum*-based memristors may provide means of implementing hybrid hardware-wetware systems for CM (Waypoint 3). Within the chapter, a method of generating musical responses using *P.polycephalum*-based memristors was presented (Waypoint 4). It was also demonstrated that the organic components could be used in near real-time musical application and could be taken outside of the controlled laboratory environment (Waypoint 5). Such achievements were a significant step forward from the work presented in Chapter 4. Thus, the research presented in this chapter has further addressed **RQ1**, **RQ2**, and **RQ3**.

6

Physarum polycephalum Memristor Development

6.1 Chapter Overview

Research in this chapter further studies *P. polycephalum*-based memristors for CM. These investigations are focused on addressing the issues that arose from the research presented in the previous chapter. Firstly, the text details measures to overcome some of the constraints of using *P. polycephalum* as an electrical component. Here, the development and testing of more rigours methods of implementing the memristors are presented.

The second half of the chapter documents a new approach to encoding and decoding musical information on memristors. This method of generating musical responses takes inspiration from a comparison between a memristor's behaviour and the way neurones communicate in the brain. The last sections talk on the composition and technology behind *BioComputer Rhythms*. The structure of this chapter is as follows:

- 6.2 - Introduction
- 6.3 - Receptacles for Culturing *Physarum polycephalum*-based Memristors
- 6.4 - An Interactive Musical Imitation System
- 6.5 - *BioComputer Rhythms*: Out of the Laboratory and into the Real World
- 6.6 - Conclusions
- 6.7 - Chapter Summary

6.2 Introduction

As the use of organic memristors is relatively new, one of the challenges it faces is the lack of consistency in measurement regimes and subsequent observations. This may largely be due to a lack of standardisation of experimental protocols both in experiment-experiment variation within the same research group and of those between groups. Such lack of standardisation is likely to be most prominent in sample-to-sample growth conditions and handling, and may be the reason certain aspects of the previous chapter's results were inconsistent with the original investigation (200). Therefore, it is of importance in future research to establish growth and experimental conditions where environmental variations, which might add experimental error to data, are better controlled or monitored. This is of great significance to both the scientific and creative aspects of this investigation.

Research presented in the previous chapter established that *P. polycephalum*-based memristors could be used to generate responses to musical seeds. Moreover, it was demonstrated that the technology could be taken outside of the laboratory and used in real-world applications. By immersing a system that encompasses *P. polycephalum*-based memristors into the real-world, it was possible to identify some limitations that needed to be addressed to progress with the research. To recapitulate, these constraints were mainly associated with harnessing living biological entities in systems for real-time application, which included organism lifespan, the delicate and time-consuming nature of the setup, and component-to-component response variation, to cite but three. When deployed in CM these constraints manifested in limited response repeatability, time constrained rehearsals and performances, and lengthy and tedious preparation procedures. Thus, before further advancing musical task models that flesh out the memristive abilities of *P. polycephalum*, the component itself needs to be refined.

Research in this chapter first reports on a method to address the limitations of encompassing *P. polycephalum*-based memristors in music technology. Here, rather than growing *P. polycephalum* in a Petri dish and allowing it to grow in a random manner towards the food source, a receptacle is designed to delineate the growth of the components. Such receptacles aim to speed up production time, protect the organism, increase lifespan, and standardise measurement regimes and subsequent observations.

6.3 Receptacles for Culturing *Physarum polycephalum*-based Memristors

An obvious avenue to go down when designing the receptacles would be to adapt techniques from microfluidics. Microfluidics is where structures such as wells, channels and tunnels are often made using a gel-like biocompatible silicon elastomer material called polydimethylsiloxane (PDMS). PDMS is durable, chemically inert, non-toxic, hydrophobic, and transparent (216). However, the polymer is expensive and requires some expertise to create moulds and cure before it can be used. As one of the key criteria for this research is accessibility to computer musicians, it was decided to explore using 3D printing techniques to fabricate the receptacles. In major part, commercially available 3D printers use the additive stereolithography fabrication method where objects are constructed by layering plastic. These machines use rolls of inexpensive filament that are available in a variety of materials. The work presented in this thesis used a Lulzbot Taz 5 stereolithography printer and Autodesk's free 123Design software.

The organism is required to forge a connection between two electronically isolated electrodes in order to use the tube as an electronic component. Thus, the tube cannot reside on an agar substrate due to it being a conductor. The organism does, however, require a high level of humidity. To achieve these requirements two chambers were designed that connected via a tube. This tube is interchangeable to allow for the effect of protoplasmic tube length on memristance to be investigated. The chambers have a well to accommodate 1.5mL of agar to achieve a favourable level of humidity. To delineate the growth of the protoplasmic tube, the chambers were fabricated with High Impact Polystyrene (HIPS) as the organism does not like this substance (217). Consequently, the plasmodium will be discouraged from growing on the walls of the chamber and encouraged to propagate across the linking tube to the other chamber, laying down the desired protoplasmic tube. HIPS is a common and inexpensive 3D printing material that prints with low warping.

As the plasmodium does not like propagating over bare metals, it was decided to avoid using metal electrodes in favour of more biocompatible materials. Perhaps one of the most popular biocompatible conductive polymers is poly(3,4-ethylenedioxythiophene):poly(styrene sulfonate) (PEDOT:PSS). In previous *P. polycephalum* memristor

Figure 6.1: A screenshot (left) and photograph (right) of the receptacle. Shown is two identical growth chambers, two lids (one with and one without an air hole), two conductive electrode collars and a 10mm base.

experiments researchers successfully used PEDOT:PSS as electrodes in demonstrating memristance (204, 205). However, like PDMS, PEDOT:PSS is expensive and requires expertise to use: spin-coating and doping in solutions to improve its conductivity. As such, the decision was made to use a newly developed conductive polylactic acid (PLA) 3D printing material. PLA is Food and Drug Administration certified and, due to its high biocompatibility, is widely used in the medical field (218). It is also worth noting that PLA is biodegradable, which may provide means of creating an environmentally friendly device in the future. By comparison, the conductive PLA has a volume resistivity of 0.75Ω-cm, while un-doped PEDOT:PSS has a volume resistivity of 3Ω-cm, which can be decreased to approximately $3\text{x}10^{-02}\Omega$-cm when doped with glycerol (219). Using the conductive PLA, two collars were printed that slotted into the chambers. Each collar was designed with an electrical contact point and a rim to attach the linking tube between the chambers.

The linking tube was cut from off the shelf medical grade polyvinyl chloride (PVC) tubing, which is available in a variety of inner and outer tube dimensions. As the aim is to limit the organism's growth space, tubing of 4mm inner diameter and 6mm outer diameter was used. Researchers have used similar dimensions in creating environments for measuring the electrical potential difference between two loci of plasmodium connected by a protoplasmic tube (101). Figure 6.1 shows a screenshot and photograph of the receptacle design.

Figure 6.2: A photograph of the receptacles set up with different tube lengths to investigate the effect on memristance. Shown are connecting tube lengths of 2.5mm, 5mm, 15mm, and 20mm.

6.3.1 Receptacle Testing

6.3.1.1 Methods and Materials

To test the receptacle, 5 samples were set up using a 10mm connecting tube. A 10mm tube length is derived from the original *P. polycephalum* memristor investigations. To date, there have been no definitive studies regarding protoplasmic tube length and memristance. Thus, to investigate this variable, an extra 4 samples of each of the following tube lengths were set up: 2.5mm, 5mm, 15mm, and 20mm (Figure 6.2). Receptacle chamber wells were filled with 1.5mL of 2% non-nutrient deionised agar. To inoculate the plasmodium into the receptacle, a colonised oat flake was placed in one chamber and a fresh oat flake in the other.

For comparison, 5 control samples were also arranged using the old experimental set up that was presented in the previous chapter (see Figure 6.3 to recapitulate). Here, two electrodes were spaced at a distance of ≈10mm within 60mm Petri dishes. Each

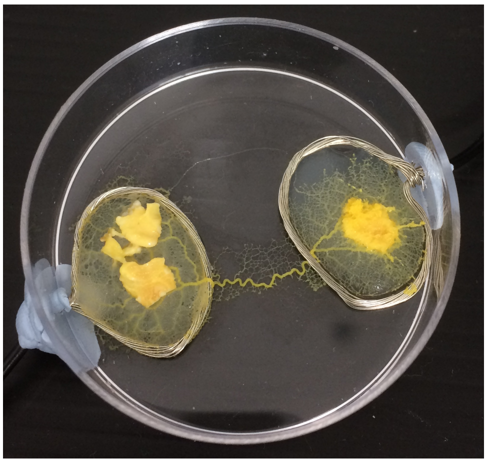


Figure 6.3: A photograph of the control samples' experimental setup. Shown is two electrodes comprised of a circle of wire filled with non-nutrient agar, linked by a protoplasmic tube. This is identical to the setup used in Chapter 5

electrode consisted of a circle (≈20mm in diameter) of tinned copper wire (16 stands at 0.2mm) filled with a 2% non-nutrient deionised agar (≈2mL).

Each sample was monitored via time-lapse imagery for the elapsed time between inoculation and forming the required protoplasmic tube. Once grown, to test the repeatability and component-to-component memristive variation, I-V tests were run on each sample using a discretised sinusoid A.C. voltage waveform of 160 steps. As the I-V footprint of a memristor is its most characteristic property, this was the most accurate way to test the receptacles. By observing each sample's I-V morphology, component-to-component memristance variation can be reviewed. In line with preceding research, electrical measurements were made using the Keithley 230 Programmable Voltage Source and the Keithley 617 Programmable Electrometer. The same software controlled each device.

Memristance is a voltage and frequency effect. The frequency of an input voltage waveform controls the size of hysteresis. That is, due to the time a system takes to respond to change across its terminals, if the frequency is too high, hysteresis lobe size will decrease. Under an increasing frequency, a memristor's I-V profile will eventually become linear. If the input voltage range is too low, the memristor's pinched hysteresis curve may become open. Thus, samples were tested under voltage ranges ± 250mV, 500mV, 5V and 10V, using voltage time-steps of Δt=0.5, 1, 2 and 2.5 seconds. Once

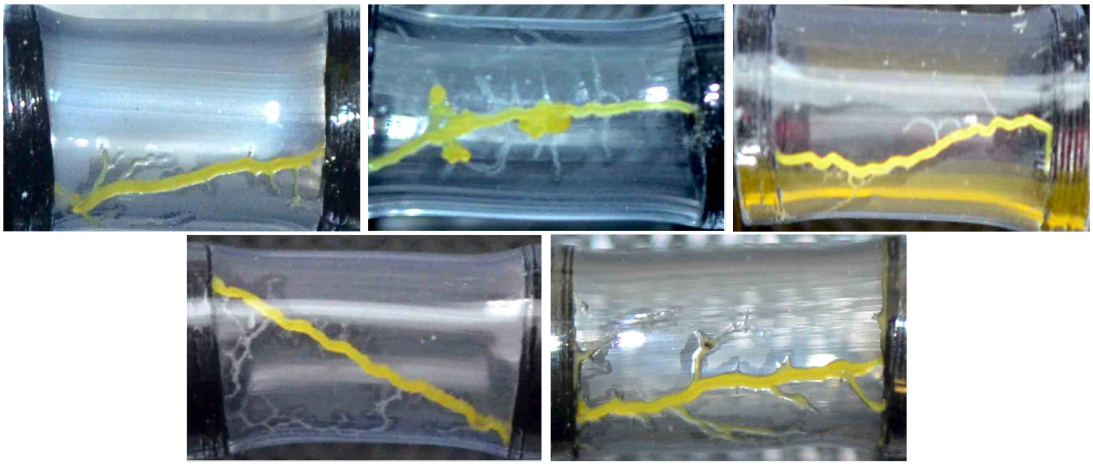


Figure 6.4: Photographs of each of the 5 10mm protoplasmic tubes grown in the receptacles.

inoculated, all samples were left in a closed draw at room temperature.

6.3.1.2 Receptacle Test Results

All of the 5 10mm samples produced the required protoplasmic tube within 10 hours of inoculation (Figure 6.4). The fastest of these grew in under 2 hours, and the longest was 10 hours, with the average growth time across all 5 samples being 7 hours 24 minutes. All of the tube length samples made the required connection within 12 hours of inoculation. Of the 5 control samples (Figure 6.5), 4 produced a linking protoplasmic tube and 1 propagated off the inoculation electrode but dried out before it made the required connection. This may have been due to the destination electrode or oat flake becoming infected and thus repelling the plasmodium. The first of the control samples took 19 hours to grow while the last took 36 hours, with an average growth time across control samples being 26 hours and 15 minutes.

As the 5 10mm receptacle samples all produced the required protoplasmic tube within 10 hours, I-V tests were run on them first at $\approx$12 hours post inoculation. Of the 5 samples, 4 presented pinched curves with the ±250mV waveform using the Δt=2 and 2.5 s time-steps. Only open curves were measured at the ±250mV range at Δt=0.5 and t=1 s. This was also the case for ±500mV. With the ± 500mV, 5V and 10V ranges under time-steps Δt=2 and 2.5 s, all 5 samples generated pinched curves. In

Figure 6.5: Photographs of each of the 4 control samples that forged the required connection between the two electrodes.

regards to hysteresis morphology, there was a strong relationship both in single sample curves measured at different time-steps and voltage ranges, and sample-to-sample curves. That is, hysteresis loops had relatively consistent lobe sizes as well as pinch locations, which is depicted in the graphs in Figure 6.6. It was noticed, however, that although hysteresis morphologies were similar sample-to-sample, there was variation in overall resistance between samples. It is possible that such variation may be a result of protoplasmic tube diameter, which was only restricted to 4mm.

With the 2.5mm samples, only open curves were measured at Δt=0.5 and 1 s under voltage ranges ± 250mV and 500mV. However, these open curves, unlike their 10mm counterparts, were very close to touching at the origin (Figure 6.7), which is indicative of an increase in memristance as a result of component shrinking. Similar results were produced with the 5mm receptacle samples with slightly larger origin offsets. At the two longer time-steps, all 2.5mm and 5mm samples produced pinched curves.

With the 15mm and 20mm receptacles, no pinched curves were measured at the two lower voltage ranges. Furthermore, at 5V and 10V, pinched curves were measured but their lobe sizes were very small. To investigate if this effect was due to the system requiring a longer time-step to respond to the ΔV due to the longer tube, measurements were taken with Δt=3 and 4 s. Under these longer time-steps, however, the pinched curve became open.

Of the 4 control samples, a total of 2 pinched curves were measured at ±250mV, both were under a Δt=2s time-step. With a ± 500mV waveform, 3 samples produced memristive curves with Δt=2s, and 2 with a Δt=2.5s. All 4 samples produced pinched

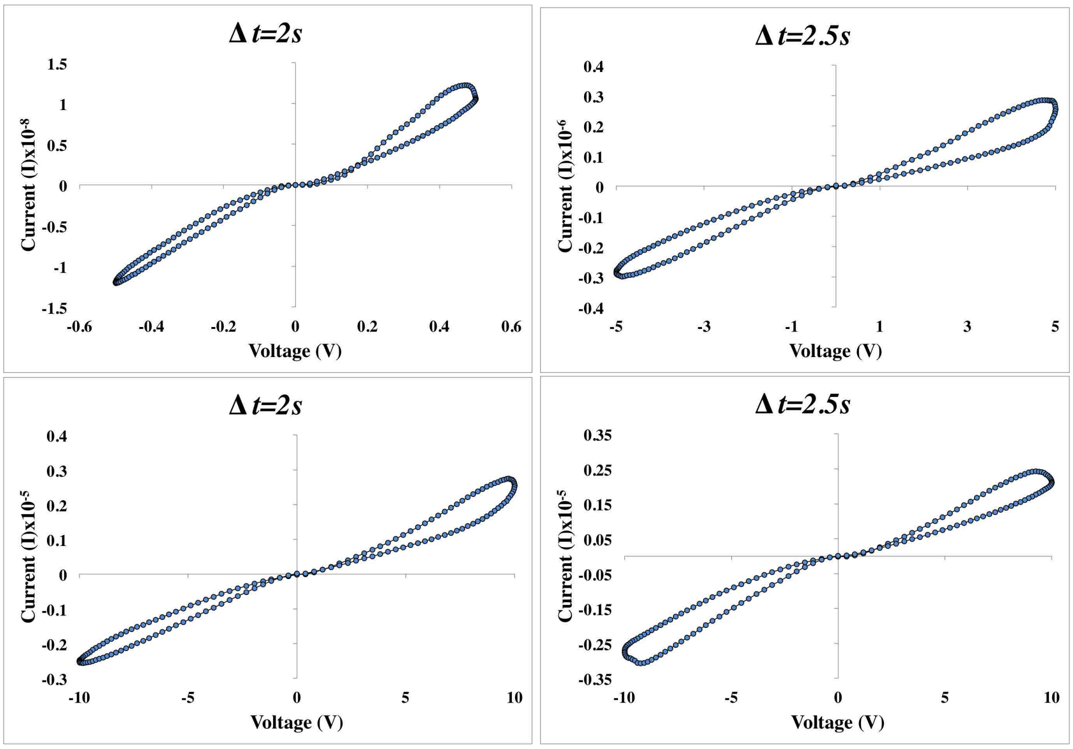


Figure 6.6: Four examples of pinched I-V curves measured on the 10mm receptacle samples. Notice how each curve is morphologically similar in regards to location of pinch points and lobe size.

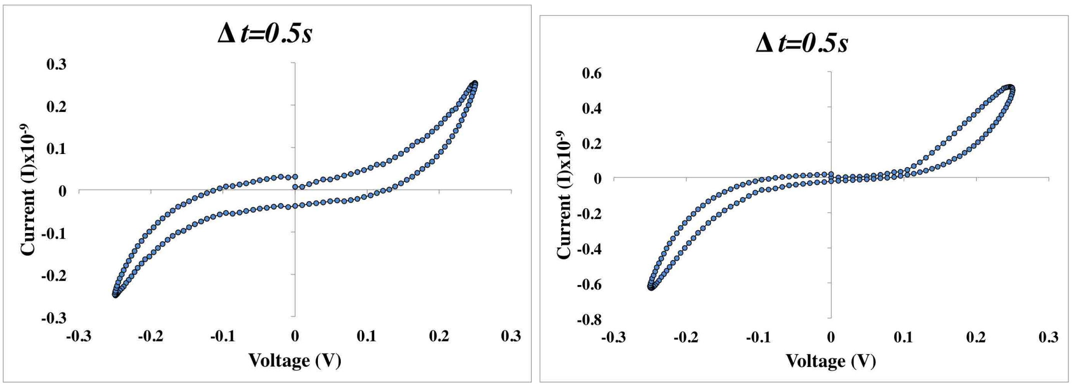


Figure 6.7: Two I-V graphs recorded under the lowest voltage range (250mV) and quickest time-step (Δt=0.5). The left graph was recorded using a 10mm receptacle, and the right graph using a 2.5mm receptacle. The 2.5mm receptacle's profile was closer to touching at origin under these test conditions.

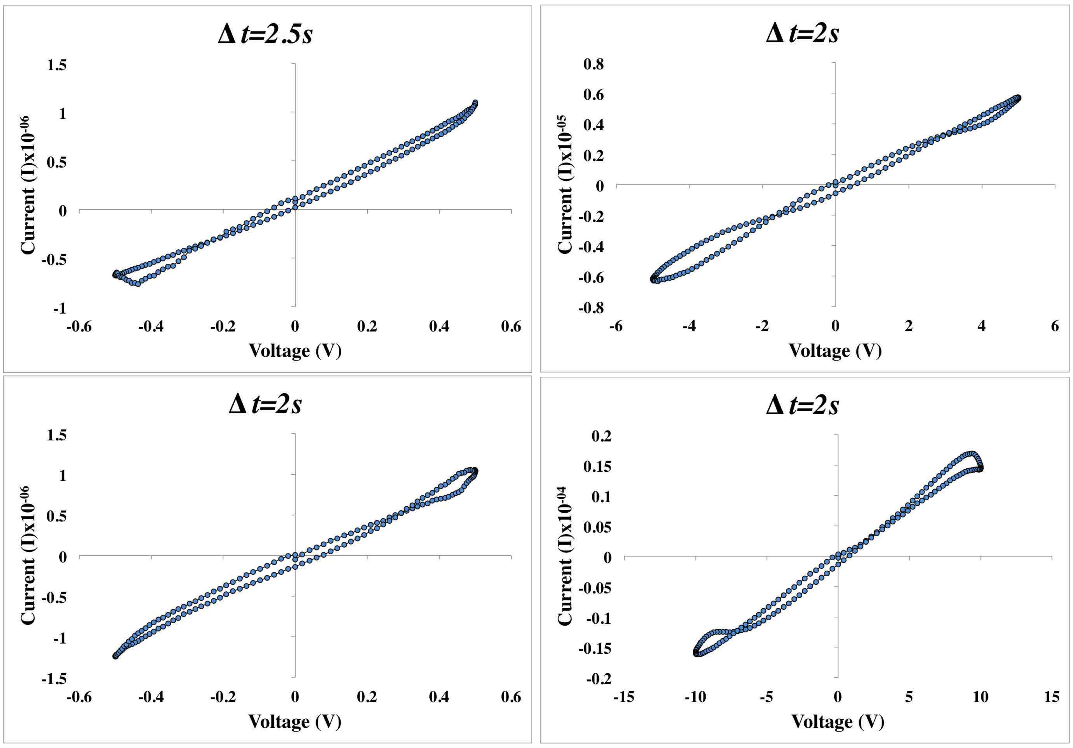


Figure 6.8: Four pinched I-V curves measured on the control samples. Results with these samples presented a high degree of variation sample-to-sample. Furthermore, in several cases, the memristive curves had several pinch points, as depicted in the two right-hand side graphs.

curves under both 5V and 10V voltage ranges using Δt=2 and 2.5 s. At lower time-steps, only open curves were recorded. Each control sample's I-V curves measured at different time-steps and voltage ranges were morphologically similar. However, a comparison between I-V curves measured across control samples show a lot of variations both in pinch point location and hysteresis lobe size (Figure 6.8). In a number of the I-V tests, the control samples produced curves with multiple pinch points: a phenomenon that was not present in any of the receptacle results.

After the initial I-V measurements had been completed, each sample was monitored over the proceeding days to investigate component lifespan. Measurements were taken on each sample once a day until they presented no memristive curves. Of the 4 control samples, 2 dried up and lost their memristive curves within 2 days of initial testing while the remaining 2 continued to record pinched curves for a further 2 days.

The lifespans of the 10mm receptacle samples were a lot longer than expected. Here, all samples maintained their memristance for at least 7 days, with 3 samples reaching twice that. Such a difference in lifespan is likely due to the receptacles being a small and enclosed space, which retains humidity produced by the agar for longer than the 60mm Petri dishes. Furthermore, in the case of the control samples, when food on the two islands became exhausted the organism would often discontinue the tube connecting the two electrodes in favour of foraging elsewhere (Figure 6.9a). Samples grown in the receptacles did not have this ability and could only span the inner circumference of the connecting tube. As the organism optimises its network over time (220), once the inside of the tube was coated the organism would optimise its connection between the two chambers creating a single tube once more. It was noticed that as time went on, each of the receptacle sample's protoplasmic tubes became thicker and stronger in colour. In hand with the increase in protoplasmic tube diameter, there was also an overall decrease in resistance in the I-V measurements, with some samples measuring in the $\text{Ax}10^{-04}$ range for 10V runs against $\text{Ax}10^{-05}$ in their earlier tests. Such an observation supports earlier thoughts on protoplasmic tube diameter affecting overall resistance.

6.3.2 Discussions

By comparing the graphs in Figure 6.6 with those in Figure 6.8, it is clear that the I-V measurements performed on samples grown in the receptacles have less variation across runs than the control samples. As a result of their pinch points not being at the point of origin, control samples' I-V curves were highly asymmetrical. This was also the case in the preliminary memristor experiments that were presented in the previous chapter. For a memristor to be considered 'ideal' hysteresis pinch points should be at 0 voltage and current. In (221), Chua explains that if such an offset of hysteresis pinch points from the origin can be modelled by the addition of circuit elements, then the device is classified as an imperfect memristor. In the previous chapter it was suggested that pinch point offset is likely due to the plasmodium producing an internal current source as a result of its intracellular shuttle streaming, which was based on Gale et al.'s (200) theoretical analysis of the protoplasmic tube as an active memristor. Here, the organism oscillates a fluid cytosol endoplasm containing ions such as Ca^{2+} and

(a) One of the control samples pictured in Figure 6.5 4 days after initial testing.

(b) One of the receptacle samples pictured in Figure 6.4 10 days after initial testing.

Figure 6.9: Photographs of a control (6.9a) and receptacle (6.9b) sample during the lifespan testing. 6.9a shows a control sample that has spanned its environment (shown by the white tube outlines) in search for food and eventually dried out. 6.9b is one of the control samples, which has spanned all the available space and then optimised its tube connection once more. The colour of this sample has intensified from a light yellow to a strong gold and the diameter is thicker than those depicted in Figure 6.4.

H^+ around its protoplasmic tubes (69, 71). Thus, the intracellular movement of ions creates a current, which, dependent on the direction of flow, will oppose or add to the driven current causing the pinch point offset. Gale et al.'s (200) analysis modelled *P. polycephalum*-based memristors as a two port 'black box' that contains a battery and memristor.

I-V profiles measured on the control samples are interesting (Figure 6.8) because several of them had seemingly randomly placed pinch points and, in many cases, multiple pinches. In theory, the shuttle streaming process described above could explain this phenomenon, where changes in streaming direction result in an extra pinch. For reference, shuttle streaming switches polarity at intervals ranging from a few seconds to a few minutes with an average interval of approximately 1.3 minutes (75). However, this does not explain why the receptacle tests were more reminiscent of an 'ideal' memristor's footprint (Figure 5.2), where pinch points were always singular and almost consistently at 0 voltage and current (Figure 6.6).

Following these results, it was possible to postulate a theory regarding the memristive mechanism in *P. polycephalum*. Researchers have proposed that voltage-gated ion channels control the current and actin-myosin contractions in *P. polycephalum* (98), which is common in a myriad of biological systems. Ion channels are small pore-like structures made out of proteins that reside in the cell membrane. These structures regulate the flow of certain ions across the membrane. Voltage-gated ion channels are activated by a local change in membrane potential. Potassium voltage-gated ion channels have been proven to play a role in memristance in plants (201). Furthermore, researchers have suggested that the Hodgkin-Huxley Axon (222) (a model that describes the initiation and propagation of action potential in neurons) comprises a potassium ion-channel memristor and a sodium ion-channel memristor (223, 224). Thus, it may be the case that the test voltage waveform is activating one or more of these channels, causing the plasmodium to take in or expel ions. This process could be how the plasmodium switches between high and low resistance states. Furthermore, if ion channels do indeed control actin-myosin contractions, then the change in tube diameter may also alter the tube's resistance.

The receptacles have delineated component morphology, which is likely to have created memristors with more consistent internal and external components. These components are also more prone to be in good contact with the electrodes. The control samples, however, were left to span a larger environment freely, resulting in vastly different components. Therefore, control samples are likely to have differing quantities of biological components, with different spatial configurations, some of which will not be in good connection with the electrodes. That is, control samples, due to their freedom of movement, will have created complex networks of protoplasmic tubes between the electrodes (as depicted in Figure 6.5). Subsequently, the applied voltage may undergo varying magnitudes of resistance to reach biological components located in different parts of the organism. As a result, the test voltages may be activating multiple ion channels at varying magnitudes. This theory is supported by the fact that all I-V curves measured on the same control sample were qualitatively similar, whereas sample-to-sample comparison shows a great deal of variation (Figure 6.8).

Results from the tube length tests were indicative of memristance increasing as a function of device shrinkage. Such a phenomenon may be due to the protoplasmic tube's field increasing as its length decreased and the testing voltage stayed the same. Here, memristive effects began to dissipate with the longer tube samples. It is likely that the longer tube lengths require a higher voltage to produce pinched curves. Although tubes at these lengths are not practical as memristors both in terms of space and the likely energy needed to use them, being able to grow longer tubes using the receptacles has other useful applications. In (123) and (207), researchers explored using the protoplasmic tube as wires that are capable of passing both digital and analogue voltages. Investigators of both these studies expressed the issue of being able to grow protoplasmic tubes at lengths between two designated terminals. The receptacles presented in this chapter may provide a possible solution to such an issue.

With the presented receptacles, more consistent, robust, and rigorous methods of implementing *P. polycephalum*-based memristors have begun to be established. Results from the receptacle testing are more uniform and repeatable than previous experimentation. Having achieved a more stable component, it is possible to now investigate the mechanisms behind the organism's memristive abilities. By gaining a better understanding of the parameters behind the organism's memristance, it may be possible to gain dynamic control over it. For example, *P. polycephalum* is responsive to certain wavelengths of light, temperature, pH, various chemicals, and pressure. In regards to this research's musical intentions, I-V curves measured with the receptacles are very similar sample-to-sample. Thus, by integrating the receptacles into the musical systems, the musicians will have superior control and repeatability against the previous implementation presented in the preceding chapter. However, if it is possible to gain more control over *P. polycephalum*-based memristors, a user could program the components to respond in different ways. For example, they could be programmed for different styles of music or different instrumentation.

6.4 An Interactive Musical Imitation System

So far, research in this chapter has established more consistent, robust, and rigorous methods of implementing *P. polycephalum*-based memristors through the design of purpose-made receptacles. Such a device also facilitates the component's integration into circuitry. These developments have overcome a large majority of the constraints that were highlighted during the experiments presented in the previous chapter. Such success has rendered *P. polycephalum*-based memristors more accessible to non-experts. Furthermore, the receptacles make up a platform to develop more appropriate encoding methods to represent musical information on memristors and task models —the process by which the system processes and generates music —that flesh out their intrinsic properties. This section presents a new method for generating musical responses using memristors. Such an endeavour takes the form of an interactive musical imitation system that generates complete responses by encompassing four *P. polycephalum*-based memristors.

One area of memristor research I was keen to take inspiration from for music generation is the comparisons between the component's behaviour and certain processes in the brain. Such comparisons have led to perspectives that the memristor may be able to revolutionise artificial intelligence (AI) (174, 225): a field that has provided a lot of tools for computer-aided composition systems (226).

Numerous publications (e.g. (227, 228)) draw comparisons between the memristor and the way synapses function: the structure that allows neurones to transmit and receive signals from one another. In particular, the component's behaviour has been found to be relatable to Spiking-Time-Dependent Plasticity (STDP) in neural networks (229), which is the procedure where synapses alter their connection weight between neurones. STDP functions by one neurone sending an electrical spike to another neurone. The receiver neurone's synapse evaluates the importance of the incoming signal by contrasting it with its own state that it stores locally and the strength of the connection between the two neurones. The synapse then updates its state accordingly and sends the result of the comparison to the body of neurone two, which may fire an impulse to another neurone (Figure 6.10). This process propagates across a neuronal network, which gives rise to complex spiking observations (230) and facilitates Hebbian learning.

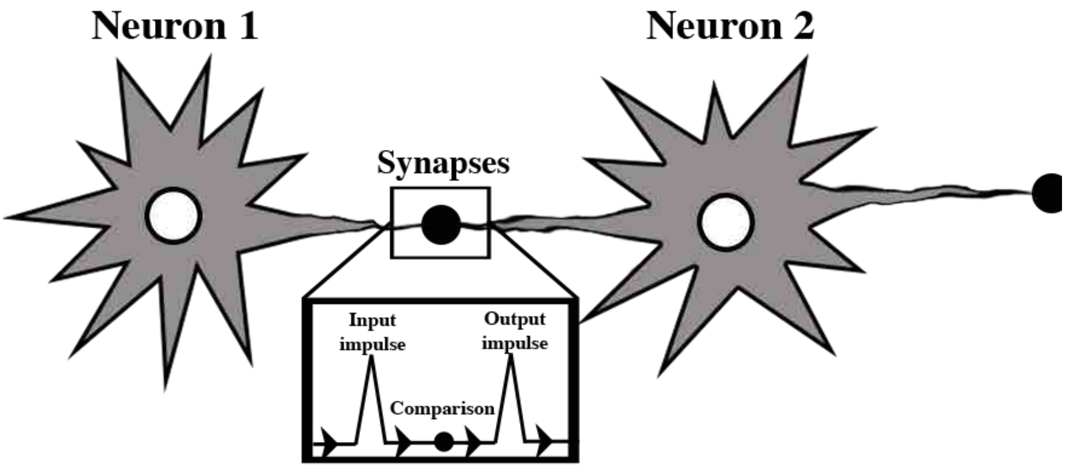


Figure 6.10: The flow of information between two neurones.

STDP-like behaviour in memristors is an interesting concept to apply to the task of music generation because the process involves transitioning non-linearly between resistance states according to a memory that goes beyond the previous state (173). Thus, the memristor's state alters according to both its history of inputs and the current input, which is relatable to the process of composing and improvising musical melody movements. However, implementing networks of *P. polycephalum*-based memristors was beyond the research's stage of development. As such, it was decided to draw inspiration from the communication process between two neurones, where the sending neurone represents system input, the receiving neurone is the system's output, and a *P. polycephalum*-based memristor represents a synapse between them. Here, a musical system was envisaged where a memristor's output would trigger musical responses by transitioning between resistance states as a function of incoming electrical impulses that are representative of musical events. By comparison, the electrical impulse sent by neurone one would be an encoded musical event, where the magnitude of the impulse corresponds to the event's popularity in the input. Thus, the receiving neurone's synapse would be evaluating the importance of the impulse against its memory and altering its state based on how often the musical event had occurred in the input. The output of the memristor, once decoded, would form part of the system's response. Figure 6.11 puts this concept into the practical terms of *P. polycephalum*-based memristors and the electrical measurement equipment.

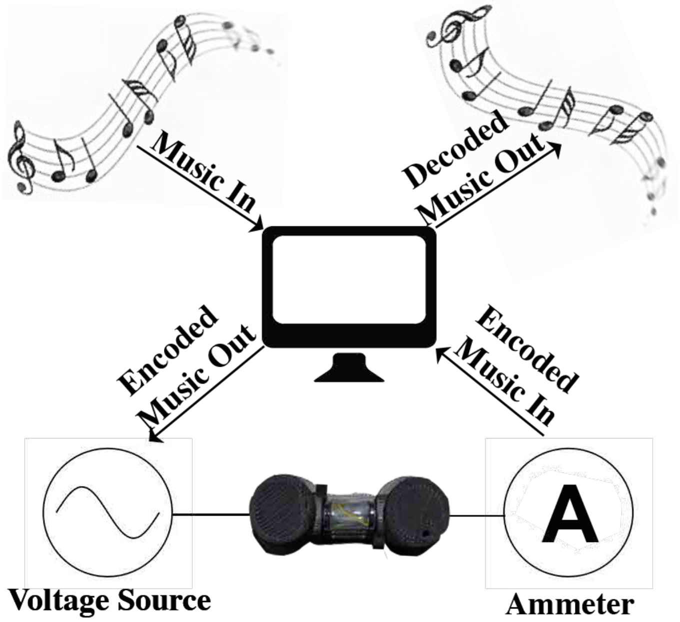


Figure 6.11: An overview of the flow of information for the interactive music system.

By encoding musical data as a function of their occurrence, the memristor's response time can be a useful feature instead of a limitation: this attribute can be harnessed to help regulate the occurrence of less popular musical events in the output. Furthermore, the function can be augmented by taking advantage of the way the component responds to reductions and increases in current. The transition between popular and less popular notes can dictate whether the input current increases or decreases, and, as such, whether the less popular note occurs in the output.

6.4.1 System Design

To implement this system, software was developed that, like the system presented in the previous chapter, works with MIDI information for musical input. The MIDI protocol allows for ease of input for both live musicians and pre-composed material in the form of MIDI files. To exemplify the music generation process in this description of the system's design, Bach's Gavotte en Rondeau is used as an example piece of melody (Figure 6.12).

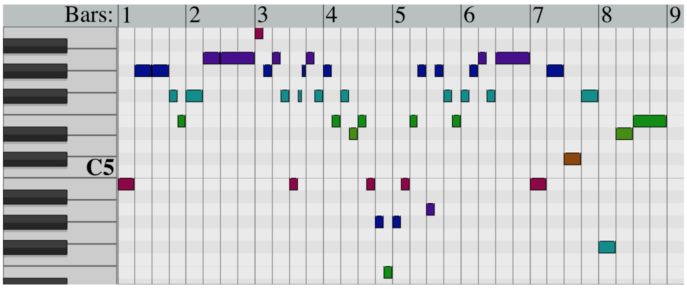


Figure 6.12: The input notes from Bach's Gavotte en Rondeau.

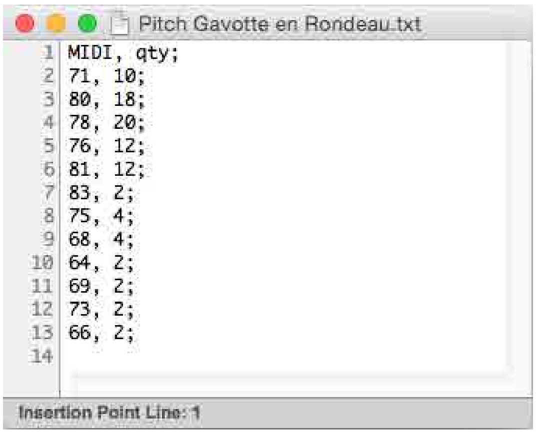
To initiate the system, the user needs to set up a listening window, which can either be set to a user-defined duration or to the length of an input MIDI file. The listening window's function is to give the system time to generate sufficient response data before it begins to output. While listening, the system generates responses and saves them into a buffer until the window finishes. Once all the input material has been processed, the system either stops or starts processing its own output, depending of the choice of the user.

While in the listening mode, incoming MIDI information is split into four data streams of pitches, durations, loudnesses, and time between note-ons. The two time-domain attributes, durations and time between note-ons, are rounded to the nearest 100th millisecond, which quantises the incoming values for processing. To enable the software to assign voltages to musical events according to popularity, it records the distribution for each of the incoming data streams. The MIDI pitch distribution for Gavotte en Rondeau is displayed in Figure 6.13.

In conjunction with the distributions, the system also maintains a count of the total amount of musical events. These values are used to distribute a voltage range of 10V amongst each of the recorded musical events where higher occurrences are assigned lower voltages. This is calculated as follows:

$$ImpulseVoltage = VoltageRange - \left(\left(\frac{VoltageRange}{TotalCount} \right) \times EventOccurrence \right) \quad (6.1)$$

For example, if the MIDI notes 60, 70, and 75 had occurred 1, 4, and 5 times, the software would assign them 9V, 6V, and 5V, respectively. The subsequent voltages make up the system's vocabulary of impulses, which are continually updated as new MIDI data comes in.



```
MIDI, qty;
71, 10;
80, 18;
78, 20;
76, 12;
81, 12;
83, 2;
75, 4;
68, 4;
64, 2;
69, 2;
73, 2;
66, 2;

```

Figure 6.13: The MIDI pitch distribution for Bach's Gavotte en Rondeau (Figure 6.12). The left column is populated with MIDI notes while the right column lists their respective occurrence.

Upon new musical events being input, the system updates the voltage distribution and calls the current event's updated impulse voltage. This value is passed to a function that manages the input into the memristors, which is designed to take advantage of the organism's non-linear resistance profile. *P. polycephalum* components exist in a low resistance state when the voltage is increasing in magnitude and a high resistance state when the voltage is decreasing. Here, if the new event has occurred less than the preceding, the function increases the previous impulse by the event's voltage. Conversely, if the event is less popular, the previous impulse value is decreased by the voltage. Thus, when moving from a lower occurring transition to a higher one, the change in current will be greater. Once the system has calculated the voltage change for each of the four parameters (pitch, duration, loudnesses, and time between note-on), it co-ordinates the input and output process to the memristors. The voltage impulse sequence for Bach's Gavotte en Rondeau is displayed in Figure 6.14. If the voltage input reaches a predefined magnitude threshold, the system momentarily halts and starts the impulse sequence again from 0v. This function protects the components from voltage overload.

The system encompasses four *P. polycephalum*-based memristors (Figure 6.15) that are assigned to pitch, duration, loudness, and time between note-ons. For this system, the electrical input and output devices are doubled up to enable the use of two memristors at any one point. Memristors are also wired into a USB relay board that

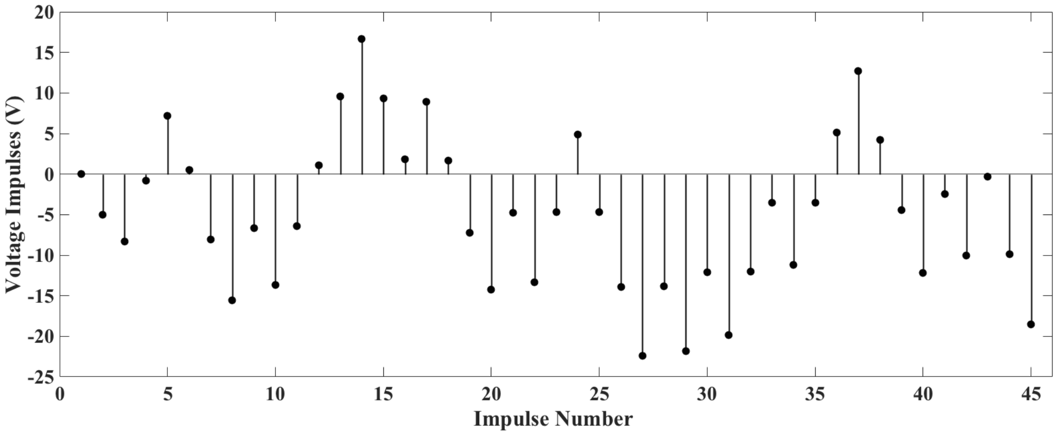


Figure 6.14: The voltage impulse sequence for Bach's Gavotte en Rondeau (Figure 6.12).

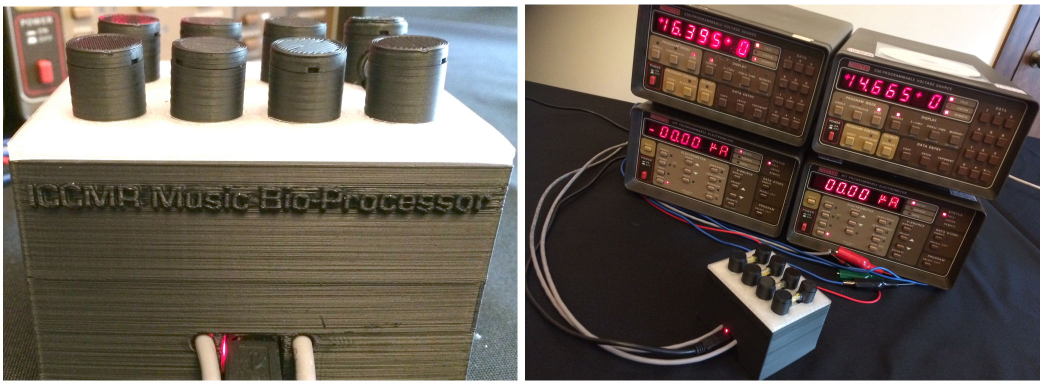


Figure 6.15: Photographs of the hardware setup showing the four Keithley instruments and the 3D printed *PhyBox*.

facilitates switching between the four components. To make the system's design robust and portable, a 3D printed box —coined *PhyBox* —was designed that houses the four memristor receptacles and the relay board (Figure 6.15). These boxes allow for the receptacles to be easy clipped in and out of the circuit, providing means of quick memristor replacement.

The system works with the memristors in pairs. First, the voltage impulses for pitch and loudness are sent simultaneously to their respective component. Then, interfacing with the electrometers, the software takes an instantaneous current reading from each of the two memristor's drain terminals. After which, it switches to the remaining two memristors and repeats the same procedure.

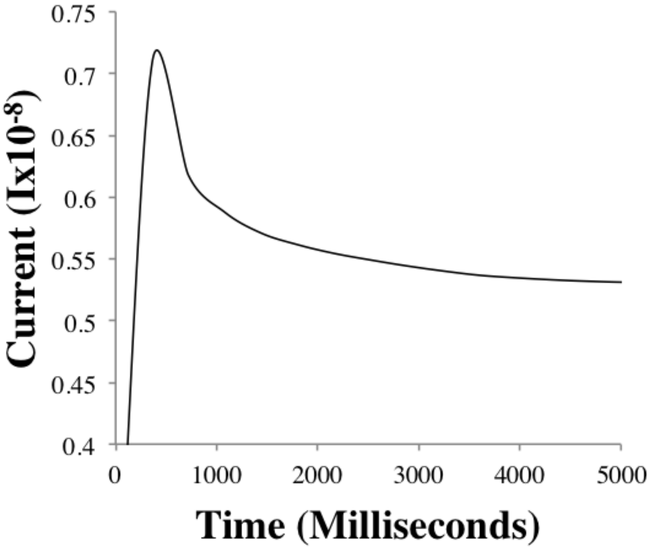


Figure 6.16: An example of a *P. polycephalum*-based memristor's response to a sudden change in voltage.

There are two user-defined parameters that control the current reading process: a step dwell time value (milliseconds) and a measurement offset percentage. The step dwell time informs the system of how long the impulse voltage is applied to the memristor before switching, and a measurement offset percentage dictates when to take the current readings after voltage onset. These two parameters allow the user to have control over the system's output. Figure 6.16 shows a *P. polycephalum*-based memristor's response to a change in voltage. This graph shows a sharp spike followed by a decay and eventually a sustained level of current. By examining this figure, you can see that the shorter the dwell time and measurement offset, the less time the memristor has to respond to the voltage change. Therefore, these two parameters dictate where on Figure 6.16's graph the system takes the current reading.

To decode the current measurements into responses, the software maintains a transition matrix of inverted percentages for each of the four MIDI data streams. Here, each of the current readings is compared against its predecessor to calculate a percentage difference value. The software then looks up the transition percentages belonging to the input musical event associated with the electrical impulses and selects the transition whose number is closest to the current reading's percentage difference value. By taking this approach, the system can only generate note transitions that have occurred at least once before. The four parameters (pitches, durations, loudnesses, and time between note-ons) are combined to produce an output musical event.

Figure 6.17 shows the input material and subsequent responses for Bach's Gavotte en Rondeau. In this case, different dwell times and measurement offsets were used. The system was set up to generate responses using dwell times of 2-seconds and 4-seconds, and offsets of 50% and 75%. By studying the note distributions in Figure 6.17, it is clear that the longer dwell time and offset responses produced music that is more reminiscent of the input. This is because the system is allowing the memristor more time to respond to a change in voltage across its terminals. Thus, the shorter dwell times and measurement offsets are likely to cause larger differences between successive current readings (as shown by the graph in Figure 6.16). In turn, elevated difference values will cause the system to output less popular transitions, which, dependant on the distribution of the input material, could result in somewhat repetitive responses. Such a phenomenon could also explain why the first two responses in Figure 6.17 are significantly longer than the input. In all three cases, the system responded with fairly static note durations, which is likely due to the input durations being rounded to the nearest 100th millisecond. A video demonstration of the musical imitation system can be found on Appendix 1.

6.4.2 E.G. Installation

The musical imitation framework was featured as a three-day installation during the 2016 E.G. conference[1], in Carmel-by-the-sea, North America. E.G. is a yearly event established to promote creative innovation across all industries. We were invited to attend this conference by BBC Earth, who were demonstrating a selection of novel technologies at the event.

For this installation, an unaltered version of the interactive musical imitation system was developed into a user-friendly application with a front end and iPad controller. A simple and intuitive user-interface was created that allowed for conference attendees

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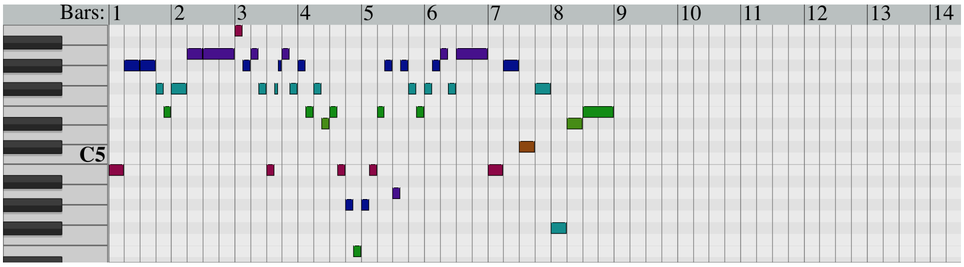
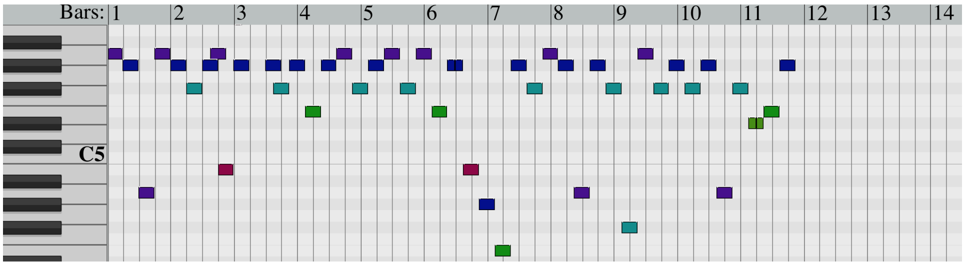
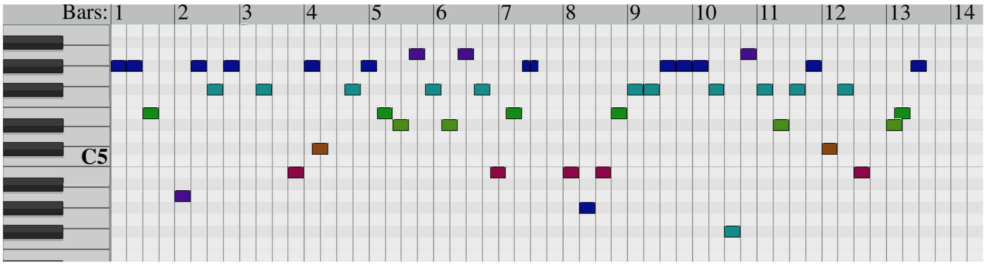
[1] `http://www.egconf.com/eg-2016` (Accessed: 13 November 2016)



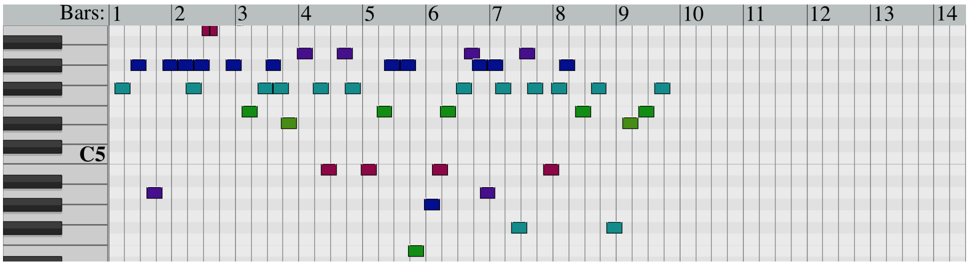
(**a**) Input notes from Bach's Gavotte en Rondeau.



(**b**) Dwell time 2-seconds, measurement offset 50%.



(**c**) Dwell time 2-seconds, measurement offset 75%.



(**d**) Dwell time 4-seconds, measurement offset 75%.

Figure 6.17: Three examples of the system's responses to Bach's Gavotte en Rondeau.

to experiment with the system. For input/output, a Yamaha Disklavier[1] piano was leased. Disklaviers are MIDI-controlled acoustic pianos that are fitted with electronic sensors for recording and electromechanical solenoids for playback; the solenoids move the keys and pedals, as if a pianist was playing the instrument. The installation was set up to allow the conference attendees to freely experiment with the system by inputting MIDI data on the piano and listening back to the system's response.

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[1] `http://uk.yamaha.com/en/products/musical-instruments/keyboards/disklaviers/` (Accessed: 13 November 2016)

6.5 *BioComputer Rhythms*: Out of the Laboratory and into the Real World

As this research is committed to taking *P. polycephalum*-based memristor technology out of the laboratory into the real-world (**RQ2** and Waypoint 5), the outcomes of work presented above were rendered into a new interactive music system for a composition. Once again, this process was in collaboration with composer Eduardo Miranda, who composed a sequel to the *BioComputer Music* piece, *BioComputer Rhythms*. This composition premièred at the 2016 Peninsula Arts Contemporary Music Festival[1], Plymouth University, UK. The piece was also performed at the Symmetry Festival 2016[2], Vienna, Austria.

6.5.1 *BioComputer Rhythms* System

The *BioComputer Rhythms* system encapsulated the interactive musical imitation framework presented earlier in the chapter. The system also built on the *BioComputer Music* technology that was reported on in Section 5.6.

Firstly, let us deal with the hardware side of the system, which can be divided into three categories: input, processing, and output. The input hardware consisted of two condenser microphones that fed into a M-Audio 410 audio interface. These microphones were positioned in a stereo x-y configuration around a mini grand piano. The processing hardware comprised a laptop computer, an Apple iPad, and the Phybox set up that was presented in the preceding section. Finally, the output equipment constituted a mini-grand piano, six percussion instruments, and the MRP system. In parallel to the *BioComputer Music* setup, the piano was furnished with twenty-four of the MRP electromagnets. In addition to this, magnets were also positioned on to the six percussion instruments. Figure 6.18 is a photograph of the set up during a rehearsal of *BioComputer Rhythms*.

Custom software was developed in Max to operate the hardware. In parallel to the *BioComputer Music* system, the software consists of a bank of performer presents.

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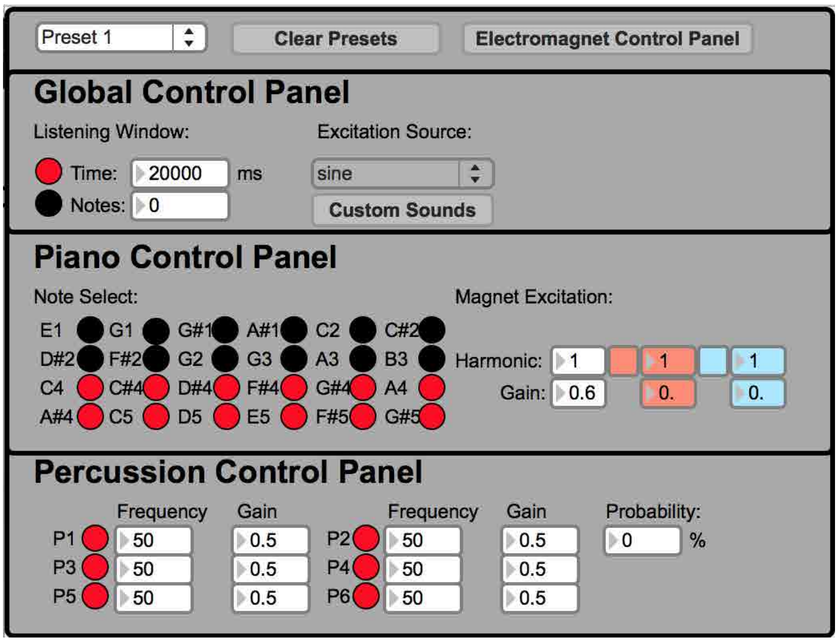
[1] `http://cmr.soc.plymouth.ac.uk/event2016.htm` (Accessed: 13 November 2016)

[2] `http://festival.symmetry.hu/programs/concerts/` (Accessed: 13 November 2016)

Figure 6.18: A photograph taken during the rehearsal of the piece *BioComputer Rhythms*. In this piece, the PhyBoxes are used to listen to a performer and generate musical responses, which are played back on the composer's piano and various metal percussion instruments through electromagnets that set the piano strings and the percussion instruments into vibration.

In contrast to *BioComputer Music*, however, such presets were not implemented to experiment with component-to-component variation, which was heavily reduced through the implementation of the receptacles (Section 6.3). Rather, they were a means of implementing different measures of composer control during the performance. Figure 6.19 is a screenshot of the composer preset interface, which was controllable via an Apple iPad. The preset controls are divided into three parameter panels: global, piano, and percussion. The function of these controls is described where relevant below.

When in use, the software operated in either a listening or playing mode. When listening, the software takes an audio feed from the microphones positioned above the strings of the piano for a user-specified window (defined in milliseconds). The listening window parameters are featured in the global panel of the composer presets. This audio signal is transcribed into MIDI information via a Fast Fourier transform (FFT) process, with the aid of piano-specific pitch templates. The MIDI transcription was filtered to provide the four information streams that the musical imitation system requires: pitch, duration, velocity, and delta time between note ons. The FFT process is facilitated by a Max external object called *transcribe* (231), which encapsulates an algorithm that provides means of real-time polyphonic pitch recognition. Within



Preset 1

Global Control Panel

Listening Window:

🔴 Time: 20000 ms

⚫ Notes: 0

Excitation Source: sine

Piano Control Panel

Note Select:

E1 ⚫ G1 ⚫ G#1 ⚫ A#1 ⚫ C2 ⚫ C#2 ⚫
D#2 ⚫ F#2 ⚫ G2 ⚫ G3 ⚫ A3 ⚫ B3 ⚫
C4 🔴 C#4 🔴 D#4 🔴 F#4 🔴 G#4 🔴 A4 🔴
A#4 🔴 C5 🔴 D5 🔴 E5 🔴 F#5 🔴 G#5 🔴

Magnet Excitation:

Harmonic: 1 🟥 1 🟦 1
Gain: 0.6 0. 0.

Percussion Control Panel

		Frequency	Gain			Frequency	Gain
P1	🔴	50	0.5	P2	🔴	50	0.5
P3	🔴	50	0.5	P4	🔴	50	0.5
P5	🔴	50	0.5	P6	🔴	50	0.5

Probability: 0 %

Figure 6.19: The preset control panels for the *BioComputer Rhythms* system, as viewed on an Apple iPad.

the *BioComputer Rhythms* system, the external object operated at a sampling rate of 44100Hz, and a frame and FFT size of 4096 samples. The FFT windowing type was set to hamming. Once transcribed, the MIDI pitch data is passed through the same algorithm that was developed for the *BioComputer Music* system where incoming notes are transcribed into the range of notes made available by the composer (defined in the preset's piano panel). Duration, velocity, and time between note ons is left unprocessed. The software feeds all of this data into the musical imitation framework for processing. The subsequent responses are stored in a buffer.

When the listening window closes, the software automatically switches into playing mode. Here, the buffer's contents are addressed for playback. Each musical event that comes out of the buffer goes though an algorithm that decides whether the event sounds on the piano or is altered to play on one of the six percussion instruments. This decision is based on a probability that the composer defines in the percussion control panel. If the event is altered to play on the percussion, another random selection process determines which of the active instruments it is sent to, with each option having an equal weighting. The composer selects which of the percussion they want to be

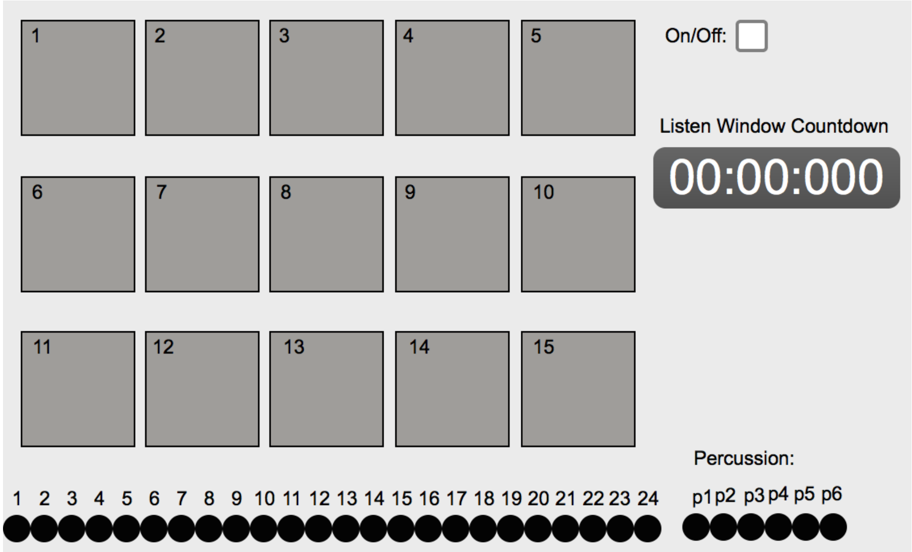


Figure 6.20: The performance interface for the *BioComputer Rhythms* system, as viewed on an Apple iPad.

available to the system in the control panel.

In playing mode, the software no longer listens to the performer but instead feeds back the newly generated responses into the musical imitation framework for re-processing. Playback mode remains active until the system is halted, or the performer activates another preset. Figure 6.20 is a screenshot of the *BioComputer Rhythms* performance interface, as viewed on an iPad. This interface displays a listening window countdown timer to inform the performer of how much time they have left to play into the system.

6.5.2 *BioComputer Rhythms* Composition

Like *BioComputer Music*, the *BioComputer Rhythms* piece was composed by Eduardo Miranda. The composition was developed to exemplify the technological advances between the two systems. Hence the word *Rhythms* being in the title of the piece, which highlights that the technology now can generate full musical responses. This aspect of the technology is further reiterated by the addition of percussion instruments, which were made a feature of during the performance by the use of spotlights (Figure 6.21).

Figure 6.21: A photograph of the stage during the *BioComputer Rhythms* performance at the 2016 Peninsula Arts Contemporary Music Festival. The lighting for the performance was set up to exaggerate the percussion instruments, which was achieved with spotlighting.

The composition consisted of 14 pre-composed movements that each had their own preset. Figure 6.22 shows an excerpt of the *BioComputer Rhythms* score. The number at the top right-hand corner tells the performer that this page of the score is to be played using preset two. At the top left of the score, there is a stave that lists the electromagnets that are active for this preset. The probability settings for the percussion are also listed along with which of the instruments are active in the preset (in this case the gong has a 5% chance of occurring). Furthermore, there is text that explains what electromagnet excitation source is programmed into the preset. Under the first bar, there is an arrow that denotes the listening window's duration, which was defined in the preset beforehand. This arrow informs the performer of what to play into the system while in listening mode. The score then goes on to dictate the accompaniment to the system's response.

6.5.3 *BioComputer Rhythms* Discussions

A recording and documentary of the *BioComputer Rhythms* piece can be found on Appendix 1. *BioComputer Rhythms* was successful in illustrating the technological advances that had been made since the première of *BioComputer Music* in 2015. The compositional process for this piece was different than that of *BioComputer Music*,

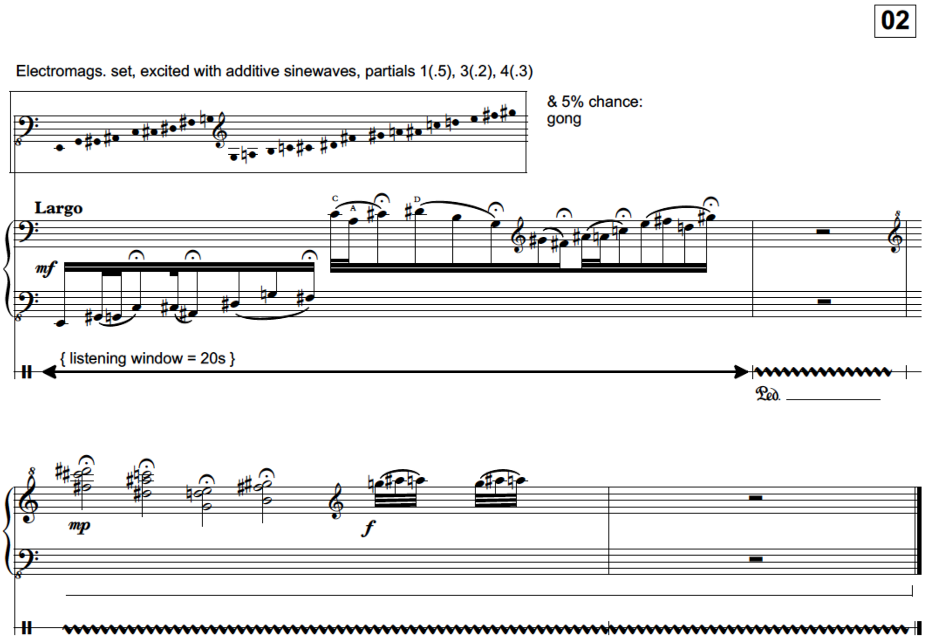


Figure 6.22: An excerpt of the *BioComputer Rhythms* score.

which is a direct result of the more advanced technology. It was possible to take better advantage of the technology's unique properties due to the standardised behaviour. Such standardisation allowed the composer to build an understanding of how to generate different types of responses by varying the input material and listening window duration. This allowed the composer to be more objective when composing the piece, which is likely to be a direct result of the receptacles that were presented in Section 6.3.

The benefits provided by the receptacles were evident throughout the process of preparing and performing *BioComputer Rhythms*. Firstly, and perhaps most importantly in regards to **RQ2** and **RQ3**, the composer was able to set up and operate the system on his own; there was little requirement for technical assistance. Furthermore, the time spent culturing the components was significantly reduced along with the quantity of components that were required. Secondly, transportability was not an issue, which was demonstrated by travelling with the system to Austria and America for performances. Here, the system was set up without the use of a laboratory and, due to the reduced growth time, all the preparations were conducted on the day of the performance.

In regards to the music, one feature of the technology that was apparent during the *BioComputer Rhythms* process is the relationship in musical progression between the input and subsequent responses. Responses have a time-based structure that is clearly based on the input but with variations in transitions between musical events. This is a result of several factors related to the algorithms and methods used in the musical imitation framework. Due to the time-gap between input and memristor processing, the responses use a matrix that is populated with transitions that occurred after the respective processed musical event. That is, the response is generated using transition data that includes events played in after the fact. This feature could provide a fruitful avenue of future work with *P. polycephalum*-based memristors for music. Here, a system could be developed that would allow the user to populate a transition matrix beforehand, either manually, or based on pre-composed music. Then, responses could be generated by the user programming in an impulse waveform. In this case, the step dwell times and measurement offsets could be programmed to vary impulse-to-impulse. It may also be interesting to generate responses by populating the transition matrix with one composition and forming the impulse wave with another.

Like *BioComputer Music*, *BioComputer Rhythms* was well received by both the general public and media. This reception helps to address **RQ4** by demonstrating that music is an effective domain to promote outreach and dissemination.

6.6 Conclusions

Currently, scientists worldwide are conducting much research into harnessing *P. polycephalum* for sensing and computation. Progress to date in regards to *P. polycephalum*-based memristors (200, 204, 205) have certainly laid the foundations for further development. However, results from these experiments have varied, causing scientists to come to different conclusions in regards to the biological function behind the plasmodium's memristive abilities. Furthermore, the majority of work with the organic component has been empirical, and, therefore, it would be infeasible to encompass it into a stable system.

This chapter presented the design and testing of a 3D printed receptacle for growing *P. polycephalum*-based memristors. The purpose of such a receptacle was to overcome some of the constraints of harnessing *P. polycephalum*-based memristors for real-time musical applications. Results from the testing of memristors grown in the receptacles showed a significant decrease in growth time, increased lifespan, and superior similarity in component-to-component responses. The receptacle also provided a protected microenvironment to encapsulate the organism for easy transportation and integration into circuitry. Using the device, it was also possible to investigate the effect of tube length on memristance. Here, results from measurements performed on a selection of different lengths suggested that memristive effects dissipate with tube length increasing.

While the application domain for this research is CM, the outcomes contribute to the field of UC more generally: the receptacle's use is not limited to CM, it could be employed to implement other hybrid hardware-bioware systems. Furthermore, the receptacle provides more rigorous methods of implementing *P. polycephalum*-based memristors with more consistent memristive observations. Thus, this area of the research is interdisciplinary in nature. As the use of *P. polycephalum*-based memristors is a new one, the challenges it faces is the lack of consistency in measurement regimes and subsequent observations. This may be due to a lack of standardisation of experimental protocols both in experiment-experiment variation within the same research group and of those between groups. Such lack of standardisation is likely to be most prominent in sample-to-sample growth conditions and handling. Therefore, if the UC community are to seriously consider using *P. polycephalum*-based memristors within practical applications and gain an understanding of its memristive properties, it is of great importance to establish growth and experimental conditions where environmental variations, which might add experimental error to data, are better controlled or monitored. With a more controlled and stable microenvironment surrounding the component, the responses produced by the plasmodium might be less variable and more predictable. The receptacle presented in this chapter goes towards achieving such standardisation. Furthermore, the progress may allow the UC community to turn their attention to studying the biological functions responsible for the organism's memristive abilities. Findings from this body of work significantly address **RQ2**, **RQ3**, and **RQ4**.

The second half of the chapter presented a new system for generating musical responses using *P. polycephalum*-based memristors. This system built on the experience from the first musical experiments where it was discovered that encoding pitches as static voltages did not take best advantage of the organism's memristive abilities. Here, instead of developing an arbitrary method of using the memristors, an approach was developed that was inspired by the component's brain-like characteristics. The new approach took advantage of the memristor's intrinsic non-linear resistance profile where musical events were assigned impulse voltages as a function of their popularity. This method of music generation produced responses where the user could define how similar the output was to the input material by altering the measurement offset and dwell time. In the final part of the chapter, the new musical system was deployed outside of the laboratory for the piece *BioComputer Rhythms* and in an installation at a major international conference. As a direct result of the receptacles, it was demonstrated that the system was highly transportable: it was taken from the UK to Austria and America. Furthermore, preparation time for concerts and rehearsals was not an issue due to the new memristor implementation methods only taking a few hours to grow.

6.7 Chapter Summary

Work in this chapter has significantly advanced the technological, scientific, and creative aspects of using *P. polycephalum*-based memristors for CM. A new memristor device has been implemented using fabrication methods that are highly practical for the majority of investigators looking to experiment with *P. polycephalum*-based memristors, thus addressing **RQ4**. This device widens the accessibility of developing prototypes with biological components to computer musicians by reducing both the setup time and complexity. These successes further add to findings from the previous chapters that address **RQ2** and **RQ3**. A new approach to generating musical responses with memristors has been introduced that exploits the component's brain-like behaviour. One of the perspectives that excite the scientific community about the memristor is the notion of building computing architectures that function in a similar way to our brains, which could have a significant impact on fields such as AI. Thus, the musical system presented in this chapter provides preliminary insights into how memristor technology may influence the future of music technology. Such insights address **RQ1**. Furthermore, the research in this chapter meets the criteria put forward by Waypoint 5.

7

Conclusions and Future Work

7.1 Chapter Overview

This chapter provides a summary of this investigation's findings along with discussions on its original contributions. The text also provides suggestions on avenues for future research with proof of concept studies.

The chapter is structured as follows:

- 7.2 - Research Conclusions
- 7.3 - Future Work

7.2 Research Conclusions

This research was a journey of exploration to investigate how *P. polycephalum* could be harnessed in CM. At the start of this study, the use of UC in CM was very much in its infancy, with little existing previous work. This state of play made it difficult to set individual goals because it was not entirely clear what the result of the study would be. Thus, the metaphor of a research journey was useful as it put emphasis on the research process, not just the end result. Waypoints were established at the start of the journey, which provided guidance and means of monitoring progress. Such an approach allowed for the investigation to move freely by not coercing progress in certain directions. This research approach is apparent through the diverse range of incrementally more complex applications that have been presented in this thesis: an algorithmic composition system, a granular synthesiser, a step sequencer, and two hybrid hardware-wetware systems for generating musical responses.

The investigation was underpinned by four questions, which guided the journey through research space. In the following sections, the findings for each of these questions are summarised and concluded.

7.2.1 RQ1: How can *Physarum polycephalum* be used in Computer Music?

RQ1 was addressed by the whole research process, and, as such, constitutes a high quantity of findings. The initial experiments presented in Chapter 4 demonstrated how, by using established Classical and Contemporary Physarum Machine methods, *P. polycephalum* could be harnessed in CM. This early stage of the research consisted of three experiments. Firstly, in Section 4.3.1, a biological realisation of a KU machine was adapted for the task of algorithmic composition. The *P. polycephalum* KU machine was originally put forward by Adamatzky in 2007 (189) and harnessed Classical Physarum Machine methods. This experiment exploited two of the organism's abilities: its autonomous decision-making and ability to form and reconfigure networks of protoplasmic tubes. Results from this experiment demonstrated that the organism's ability to dynamically reconfigure its topology can be applied to the task of sequencing musical events.

- **Contribution 1.1** —*P. polycephalum's* behaviour can be harnessed as a decision making mechanism for algorithmic composition. [Section 4.3.1]

However, the experience of implementing a CM system harnessing Classical Physarum Machine approaches highlighted several limitations. Firstly, it was clear that gathering behavioural information via time-lapse imagery was restricting due to the need to interpret the images. Furthermore, the time the organism took to exhibit enough behaviour to apply in a CM system was significant (circa 92 hours in the presented example).

- **Contribution 1.2** —Classical Physarum Machine methods are not well suited for CM due to the time the organism takes to migrate and the significant effort required to interpret images. [Section 4.3.1]

Experiment 2 moved on to investigate how the Contemporary Physarum Machine approach of implementing systems that exploit the organism's extracellular membrane potential could be applied in CM. In this experiment, the organism's bioelectrical oscillations were used as the source material within a granular synthesiser. It was discussed that using GS requires a lot of control data. Therefore, composers often implement complex algorithms that automate the production of grains according to a set of organisational parameters. This experiment investigated whether *P. polycephalum* could automate the GS process for a composer. These Contemporary Physarum Machine methods did not require human interpretation and, therefore, the behaviour could be applied in CM applications automatically by programming a conventional computer. The lead-time to gather enough data to drive the synthesiser was still significant (five days generated 200 seconds of audio data). However, this application of behaviour did provide a simple method for automating the production and spectral distribution of sound grains in GS. The method also provided means of controlling the sonic result through various means of stimulation (e.g. light and chemicals). When interacting with the bio-electrical behaviour at individual electrode sites, activity at other electrode sites changed in amplitude and frequency. Thus, the spectral arrangement of grains took advantage of the organism's ability to organise its global oscillatory behaviour.

- **Contribution 1.3** —*P. polycephalum's* bio-electrical oscillations can be used as a set of controllable audio oscillators whose outputs are related. [Section 4.3.2]

At this point in the research journey, it was clear that the time the organism takes to display the behaviour that UC researchers have previously explored is limiting when investigated for CM. With this insight, it was decided to run another initial experiment to investigate if the speed issue could be addressed while still harnessing established Physarum Machine methods. This experiment took an offline approach to harnessing the bio-electrical behaviour and drew inspiration from the successes of the previous two experiments: decision-making and the rich spectrum of electrical oscillations. Here, a software step sequencer was developed where the parameters of each step were regulated as a function of recorded electrical behaviour.

- **Contribution 1.4** —The plasmodium's extracellular membrane potential can be recorded and subsequently embedded into conventional CM tools to augment their usage. [Section 4.3.3]

Results from these initial experiments illustrated that established Physarum Machine approaches could be used to implement systems for CM using sonification and musification techniques. However, it became apparent that bespoke methods needed to be developed in order to overcome the limitations (e.g. real-time use) of the above systems and progress with the research.

- **Contribution 1.5** —*P. polycephalum's* bio-electrical behaviour can be used to implement musification and sonification systems. [Section 4.3.3]

Research in the second half of the thesis investigated the feasibility of implementing a hardware-wetware circuit to generate responses to seed music. This avenue of research was chosen after a journal article was published suggesting that the organism's protoplasmic tube could function as an organic memristor. Such a discovery was most exciting due to the memristor's processing and memory capabilities: it suggested that it may be possible to implement actual biological musical processing systems.

The first experiment that was presented investigated ways in which biologically grown memristors could process pitches to generate responses. The aim of this experiment was to gain a clear appreciation of how to best approach harnessing a memristor's input-output space for music. Thus, instead of attempting to generate complete responses straight away, the experiment focused on simple note transformation to allow for a clear understanding to be built before a complex multimodal system was developed. Here, pitch information was encoded into discrete voltages that were sent through a *P. polycephalum*-based memristor. The component's subsequent response to each input voltage was measured in terms of current, and decoded back into musical pitches in near real-time. The term near real-time is used here due to the latency between event and response. There is not a globally agreed upon threshold for classifying something as real-time. Wessel and Wright state that 10milliseconds between event and response is an acceptable upper bound for real-time musical interaction with a machine (232). Other researchers state that players can not distinguish between event and response latencies lower than 30milliseconds (233). Currently, the system presented in this thesis has a minimum response time of approximately 550milliseconds, which is due both to the Keithley instrument's conversion speed of 360milliseconds and the minimum time gifted to a *P. polycephalum* memristor to respond to a change in voltage.

This first memristor system was deployed into real-world CM application outside of the laboratory to compose the piece *BioComputer Music*. Results from these experiments highlighted that *P. polycephalum's* memristive abilities could be used to generate musical accompaniments in near real-time.

- **Contribution 1.6** —A *P. polycephalum*-based memristor can be used to generate responses to musical events in near real-time. [Section 5.5]

However, encoding musical events as discrete voltages resulted in the system's output being less dynamic than the input. This phenomenon was due to the component's response being related to the magnitude of the voltage change and the time the system takes to respond. Thus, the system's response was not based on the input transitions; rather, it was responding with notes that were assigned to central current magnitudes in the current-to-note distribution.

- **Contribution 1.7** —Generating musical responses with *P. polycephalum* memristors by encoding pitches as discrete voltages and decoding current readings into pitches does not produce an output that is based on the transitions of the input. [Section 5.5]

Through running both I-V and musical tests on several memristors, it was discovered that there was a lot of response variation component-to-component. In the piece

BioComputer Music, the composer experimented with this variation by switching between ten memristors throughout the piece.

- **Contribution 1.8** —The non-standard nature of the memristors grown in Petri dishes causes different responses to be generated component-to-component to the same input material, which can be harnessed to produce different musical response options. [Section 5.6]

The experience gained from the first CM memristor experiments provided direction to progress with the research. It was clear from immersing the previous system into the real-world that the system's robustness, ease of set up, and musical processing approach needed to be addressed. Therefore, in Chapter 6, a new memristor design was presented and tested. This device was developed to overcome some of the constraints associated with implementing biological components for the CM community. Subsequent testing showed a significant decrease in growth time, increased lifespan, and superior similarity in component-to-component responses. The results indicated that the receptacle design was appropriate for the CM community due to it being low-cost, easy to set up, and robust.

- **Contribution 1.9** —It is possible to implement CM-friendly and inexpensive *P. polycephalum*-based memristors that can be used for CM systems in the real-world outside of the laboratory. [Section 6.5]

In the final section of the thesis, a new musical system was presented that harnessed the memristor's synapse-like behaviour. In this system, instead of transcribing musical events into static voltages, input material was encoded according to how often they had occurred in the input. This approach treated the encoded musical events as impulse voltages, not as a constant applied voltage, which is in keeping with the component's synapse-like behaviour. Results from this system were more promising than the previous attempt at using memristors for music. The transitions in the output material showed good correlation to the input. It was also demonstrated that the level of similarity between the input and output could be controlled by altering the voltage impulse dwell time and the measurement offset.

- **Contribution 1.10** —The memristor's synapse-like behaviour can be harnessed to implement musical imitation systems with a similarity parameter.

7.2.1.1 RQ1 Final Remarks

RQ1 has been addressed at every stage of this investigation: each of the presented systems demonstrated a potential use of *P. polycephalum* in CM. Techniques such as sonification and musification provide computer musicians with means of creating music/sound with almost any type of phenomena. Although these techniques are powerful, it was clear after the initial experiments that if we are to understand the benefits of UC for CM, research needed to move past the sonification and musification of behavioural data. Indeed, the opportunities are likely to be far greater when developing actual hybrid hardware-wetware or inspired algorithms for music technology. With the continuing development of memristor-based technology, it may be possible to implement processing systems that function in a manner that is similar to neurological processes. These new types of technologies are likely to provide great opportunities for creative applications of technology.

7.2.2 RQ2: Is it possible to use *Physarum polycephalum* for real-world Computer Music applications outside of the laboratory?

Although the systems presented as part of the initial experiments did not directly address **RQ2**, aspects of these technologies could be taken outside of the laboratory. The algorithmic composition framework only required a culture of plasmodium and a computer to take images and implement the composition. In contrast, the GS experiment used an experimental setup that had to remain stationary to avoid electrical interference. The step sequencer application, however, could be used without a live culture of plasmodium, which was made possible by uploading a data set of pre-recorded electrical behaviour. This application demonstrated that it is possible to implement CM systems using *P. polycephalum's* bioelectrical behaviour for use outside of the laboratory.

- **Contribution 2.1** —*P. polycephalum's* extracellular membrane potential can be recorded and embedded into software systems for use outside of the laboratory. [Section 4.3.3]

By taking this approach, however, the user is unable to interact with the plasmodium's behaviour while they are composing —the only controls to alter the output are the software parameters. Thus, unless provided with a bank of recorded behaviour data sets, the sequencer's output will become repetitive. As such, in relation to **RQ2**, it is important to conclude these initial experiments by stating that none of these systems harnessed live plasmodium for real-time application. Therefore, they demonstrated that it is not feasible to harness the respective Physaum Machine methods to implement CM systems for use outside of the laboratory.

- **Contribution 2.2** —It is not feasible to implement real-time musical systems with live plasmodium for outside of the laboratory using bioelectrical and migration-based Physarum Machine methods. This is due to the time the plasmodium takes to exhibit oscillatory and migration behaviour, and the volatile nature of the set ups. [Sections 4.3.2 and 4.3.3]

The main contributions to **RQ2** were from research reported in Chapters 5 and 6. Here, it was first demonstrated that live plasmodium could be encompassed into an analogue circuit for generating musical responses. To address **RQ2**, this system was deployed for the piece *BioComputer Music*, which was composed by Eduardo Miranda. The process of providing the composer with the system for rehearsals and the performance demonstrated that live *P. polycephalum*-based memristor technology could be used outside of the laboratory.

- **Contribution 2.3** —*P. polycephalum*-based memristors can be deployed in CM systems outside of the laboratory. [Sections 5.6 and 6.5]

Although the *BioComputer Music* study was successful at using live plasmodium in the real-world, the process was still heavily dependent on a laboratory preparation procedure. Moreover, the system was volatile both in physical robustness and electrical observations. In Chapter 6, a receptacle was developed that went towards alleviating these limitations. Such a device provided a protected micro-environment that was robust, transportable, and easy to set up.

- **Contribution 2.4** —*P. polycephalum*-based memristors can be grown in a receptacle for stable use outside of the laboratory. [Section 6.3]

7.2.2.1 RQ2 Final Remarks

Although aspects of the systems developed in the initial experiments could be used outside of the laboratory and in the real-world, they could not use the plasmodium's behaviour live. Therefore **RQ2** was mainly addressed by work presented in Chapters 5 and 6. The main limitation of harnessing *P. polycephalum*-based memristors for CM was robustness. In the thesis it was demonstrated that a large amount of these limitations could be overcome by establishing measures to standardise the organism as an electronic component. Such measures were designed with CM accessibility in mind and provide a platform for developing systems that are not reliant on the user having access to resourced laboratories. Thus, to conclude **RQ2**, *P. polycephalum* does exhibit properties that can be harnessed to implement CM systems for real-world applications outside of the controlled laboratory environment.

7.2.3 RQ3: Is *Physarum polycephalum* an appropriate and practical substrate for research into Unconventional Computing for Computer Music?

As with **RQ1**, **RQ3** was addressed by the whole research journey. In Chapters 1 and 2 it was explained that UC is difficult for the non-expert to access due to its complexity and resource-intensive nature. In these sections it was suggested that such limited accessibility may be the reason why computer musicians have not really begun exploring UC. Chapter 3 gave an overview of the small quantity of existing UC for CM studies. Findings from this review further highlighted the accessibility constraint as the large majority of previous research was conducted as a collaboration between computer musicians and scientists. Thus, the work could not be built upon by the average creative practitioner.

Research in Chapter 4 explored if the behaviour that has made UC prototyping with *P. polycephalum* feasible for computer scientists and engineers also rendered the organism appropriate for CM. Firstly, it was discovered that the organism could be obtained and cultured by someone with a music technology background.

- **Contribution 3.1** —The plasmodium of *P. polycephalum* is a low maintenance biological substrate that can be sourced, cultured, and farmed by the creative practitioner. [Chapters 4, 5, and 6]

The first musical experiments explored applying popular established Physarum Machine techniques in CM applications. This process demonstrated that prototypes can be implemented inexpensively and without formal or specialist training in biology or engineering. Therefore, it is reasonable to state that Physarum Machines can be implemented by creative practitioners.

- **Contribution 3.2** —Physarum Machines prototypes can be developed by creative practitioners using low-cost equipment and openly accessible methods. [Chapters 4, 5, and 6]

It became apparent from the initial experiments that these methods were not compatible with some of the basic criteria that computer musicians expect from their technology. In major part, music technology is designed to be used in real-time. The reason for this may be that music can be seen as a method of expression, which is hard to achieve using systems that take several days to use and are slow to react to methods of interaction. Furthermore, the initial experiments highlighted issues of robustness and transportability.

- **Contribution 3.3** —Not all established methods of developing Physarum Machine prototypes are appropriate for CM. [Chapter 4]

As a result of the fast moving and large quantity of UC research using *P. polycephalum* (as presented in Section 2.6), the organism has been described as a multipurpose, or universal, UC substrate (11). Thus, *P. polycephalum* allows computer musicians to experiment with a number of different concepts that are actively being explored in UC research that may not be accessible through other substrates. This is exemplified by the diverse range of systems presented within this thesis. Although, as concluded above, some of these concepts may not be well-suited for CM, the organism provides a platform for building an understanding of what aspects of UC may be useful for music.

- **Contribution 3.4** —*P. polycephalum* is an accessible biological substrate that provides non-experts with a means of experimenting with a number of different UC concepts. [Chapters 4, 5, and 6]

7.2.3.1 RQ3 Final Remarks

The diverse range of musical experiments presented in this thesis indicates that *P. polycephalum* is an appropriate substrate to begin experimenting with aspects of UC in CM. Furthermore, the organism's low-maintenance and accessibility promotes the dissemination of UC for CM: practitioners can easily develop Physarum Machines for their own work after discovering the work of others. *P. polycephalum* has been deployed in UC for a number of different tasks. Therefore, the biological substrate also provides a platform for computer musicians to experiment with several different aspects of UC.

7.2.4 RQ4: How can this research contribute to the general field of Unconventional Computing?

Although the primary problem domain of this research was CM, the findings also benefit other fields. This investigation has demonstrated that CM is a robust and unique problem domain for research in UC. Music technology is often designed to be deployed in real-time applications; for example, composition and performance. Furthermore, in the majority of cases, creative practitioners expect to be able to transport their technology and use it in different spaces. These criteria are not normally pressing issues in UC where investigators are more concerned with laboratory proofs over real-world usability. The body of research presented in this thesis exemplified this difference in research priorities. However, the benefits of developing CM systems using aspects of UC can be seen clearly. For example, by taking UC systems out of the laboratory, issues of practicality had to be addressed. This is most clearly demonstrated by the research presented in Chapters 5 and 6 where new methods of implementing memristors had to be established to enable practical use in an uncontrolled environment.

- **Contribution 4.1** —Developing UC prototypes for CM forces the investigators to address problems of practicality that can easily be overlooked when developing laboratory prototypes. [Chapters 4, 5, and 6]

Another benefit of researching UC for CM is that music can provide an excellent method of outreach that could potentially widen interest in UC. Such a benefit is apparent from the media impact that resulted from the release of *BioComputer Music* and *BioComputer Rhythms*.

- **Contribution 4.2** —CM is an excellent application domain for disseminating research progress. [Sections 5.6, 6.4.2, and 6.5]

7.2.4.1 RQ4 Final Remarks

To the best of my knowledge, the research in this thesis is the first concentrated investigation into harnessing a specific UC substrate in CM. From this journey of exploration, it is clear that UC could benefit from applying research to a practical problem domain. By addressing the practicalities of using UC systems in the real-world it is likely that its application will widen as people are able to readily experiment. The work in this thesis has already established affordable and accessible methods of implementing *P. polycephalum*-based memristors. Thus, to conclude **RQ4**, CM research can provide several benefits to the general field of UC.

7.3 Future Work

This section discusses some areas of future research with *P. polycephalum*-based memristors, which is split into three sections: areas of further investigation to develop *P. polycephalum*-based memristors, areas to explore with the receptacles, and areas to develop the musical systems that were presented in this thesis. A set of further research questions are suggested at the end of each of these sections.

7.3.1 *Physarum polycephalum*-based Memristors

The majority of existing memristor research with the organism is empirical. Thus, to further establish the organism as an electrical component, it is necessary to start building a theoretical understanding of the mechanism behind its abilities. Such an understanding will also allow us to begin comprehending what the benefits are of using a biological entity as a memristive component along with how a more stable and standard device can be implemented. To do so it is necessary to have a detailed understanding of each of the components that make up the organism and how they integrate together. This requires building knowledge of their material structure, how they relate to each other, how they function, and what the parameters are in which they operate. These are all dynamic components and systems and, therefore, this is a critical aspect of their characterisation.

The core system that was used as a memristor in this investigation was the protoplasmic tube, the mechanism by which the plasmodium moves and distributes internal components. As detailed in Section 2.5.2, these tubes contain actin-myosin fibres that have the ability to contract rhythmically both longitudinally and radially along each tube. Such activity causes a pressure gradient to build up internally which results in the organism's innate shuttle streaming behaviour: the periodic movement of protoplasm back-and-forth. The molecular mechanism behind this phenomenon is believed to be similar to that of muscle fibres and therefore it is likely to be calcium sensitive (234).

A property of the protoplasmic tubes is that they are electrically active, as demonstrated by experiments in Chapters 4, 5, and 6. This property is the most relevant and interesting in regards to understanding *P. polycephalum*-based memristors. The fundamental unit of cellular bioelectrical activity is the action potential, first described by

Hodgkin and Huxley in 1952 (222). Here Na^+ and K^+ are transported across a membrane barrier (206). Thus, the most probable mechanism of this electrical conductivity in *P. polycephalum* is the movement of ions across a barrier. Other investigators have suggested that electrical current in the plasmodium is controlled by voltage-gated ion channels (98). This behaviour is similar to that shown in neurological systems where electrical current is transmitted along an axon as an action potential. This type of electrical event produced by a voltage-gated ion channel regulated movement across a barrier is very common in biological systems (235). For example, in neurons the ions involved in active conductance are Ca^{2+}, Na^+, and K^+ (236). Following experiments in Chapter 6, it was suggested that voltage-gated ion channels may play a role in the organism's ability to switch between a high and low resistance state. These ion channels have been studied as a memristive mechanism in a number of other biological systems (201, 223, 224). Thus, it is suggested that, in order to understand what causes the cells to switch between high and low resistance states, future investigations should study membrane ion transport. This could be achieved through using ion selective electrodes while taking I-V measurements. Due to the expertise and equipment required to investigate ion transport, it is likely that the research would need to be investigated in collaboration with biologists.

Ca^{2+} is known to play a major role in intracellular signalling, regulation of membrane conductance, and protoplasmic streaming in a wide range of cell types. In the plasmodium specifically, Ca^{2+} plays a significant role in the regulation of processes such as shuttle streaming (234) and phototaxis (96). Here, the fluctuation of free calcium in the cell is believed to be the physiological signal that initiates these processes (97). As such, it would be a sensible starting point to investigate Ca^{2+} first. Plasmodia are known to be calcium-rich. The organism stores the ion within mitochondria, endoplasmic reticula, and granules.

Another potential factor to consider is redox, chemical reduction and oxidation reactions. Redox state has been shown to regulate voltage-gated Ca^{2+} channels in neurones (237). The redox state of a cell is the cellular ratio of reducing equivalents (NADH and NADPH) to oxidising equivalents (superoxide radicals, hydroxide radicals and hydrogen peroxide) (238, 239). The redox state influences calcium uptake and release from the organism's cellular stores. When oxidative stress is low, Ca^{2+} is taken up into the granules. It is suggested that an increase in oxidants causes the plasmodium to react by increasing concentrations of superoxide dismutase (affects superoxide radicals), reduce glutathione (antioxidant) and release Ca^{2+} from its stores (97). An increase in oxidant generation causes the plasmodium to react by increasing concentrations of superoxide dismutase (an enzyme that removes superoxide radicals), reduce glutathione (an antioxidant), and release Ca^{2+} from its stores. The changes in free Ca^{2+} levels could affect the resistance state of the protoplasmic tube. In the context of the experiments presented in this thesis, when electrical energy was applied to the organism, it would likely have dissipated into many mechanisms. These could include electrical conductance (e.g. along the protoplasmic tube to the electrode) and heating effects due to resistance along the conductive pathway. Also, localised irregularities in structural components could cause high localised thermal effects. These could increase the production of oxygen radicals, causing fluctuations in free Ca^{2+} that could potentially give rise to the memristive observations. It is also possible that a change in Ca^{2+} levels as a result of redox reactions could impact the movement of Ca^{2+} through voltage-gated ion channels and also the ionic wave that propagates along the actin filaments (240). Both these processes may alter the resistance behaviour of the system.

Once the plasmodium's memristive mechanism has been discovered, it should be possible to develop methods of interaction and control over the component's behaviour. Here, it may be possible to control its degree of non-linearity, and in doing so develop robust methods to encode, store, process and retrieve digital and analogue information on the actual physical device. An exciting prospect of using biological components is that they display complexities that might be harnessed to augment their usage and implement different classes of memristors or variations thereof (221). This may be achieved by investigating the effects of certain stimuli on the cell's conductance; for example, chemicals, temperature, pH, light, and pressure. In regards to music, it is plausible to envisage a system that would produce different sounding responses by changing the hysteresis of its memristors.

Suggested questions for future work to develop *P. polycephalum*-based memristors:

- Does memristor state correlate with changes in ion concentrations?
- Does memristor state correlate with increased reactive oxygen production?

- Is it possible to alter a *P. polycephalum*-based memristor's hysteresis by subjecting the cell to certain stimuli?

7.3.2 Receptacles

The receptacles developed and tested in Chapter 6 were used solely for implementing *P. polycephalum* memristors. These devices are likely, however, to have uses beyond that of implementing a single component. For example, in (123) and (207) the protoplasmic tube was studied as a self-assembling and self-repairing biological wire. In both these investigations, the researchers expressed further work was needed to establish methods of growing the protoplasmic tube according to a scheme. The receptacles put forward in this thesis provide a method of delineating the production of the tube between two, or potentially more, points. Figure 7.1 is two photographs illustrating that the receptacles can be used to grow healthy tubes at lengths in excess of 100mm. Thus, it is suggested that future research should investigate whether the tube's data transfer capabilities alter as a function of length. Furthermore, it will also be necessary to run lifespan tests on the longer tubes.

In (207), the transfer function of the protoplasmic tube was investigated. Results from this investigation indicated that the agar required to grow the tubes may cause an issue if the organism was to be integrated into electrical system. This is due to the substrate's capacitance. The receptacles presented in this thesis still require agar to keep humidity high. However, with small changes to the receptacle's design, it is possible to create a detachable tube. This set up may allow for the tube to be disconnected from the chambers once growth is complete and clipped into an electrical system. Moreover, once the tube's health is starting to deteriorate, it could be reconnected to new chambers for food and respite until it has repaired itself and can be used again. Figure 7.2 shows a photo of long tubes that have been disconnected from the chambers. Future research will involve running tests on the protoplasmic tubes to investigate their electrical properties without the agar.

Another productive avenue of future research would be to investigate developing multi-core cable systems. The PVC tube could be replaced by one that is honeycombed into several airtight tunnels. The chambers and electrodes would need to be altered to accommodate the new tube. When choosing the new tube, it would also be sensible

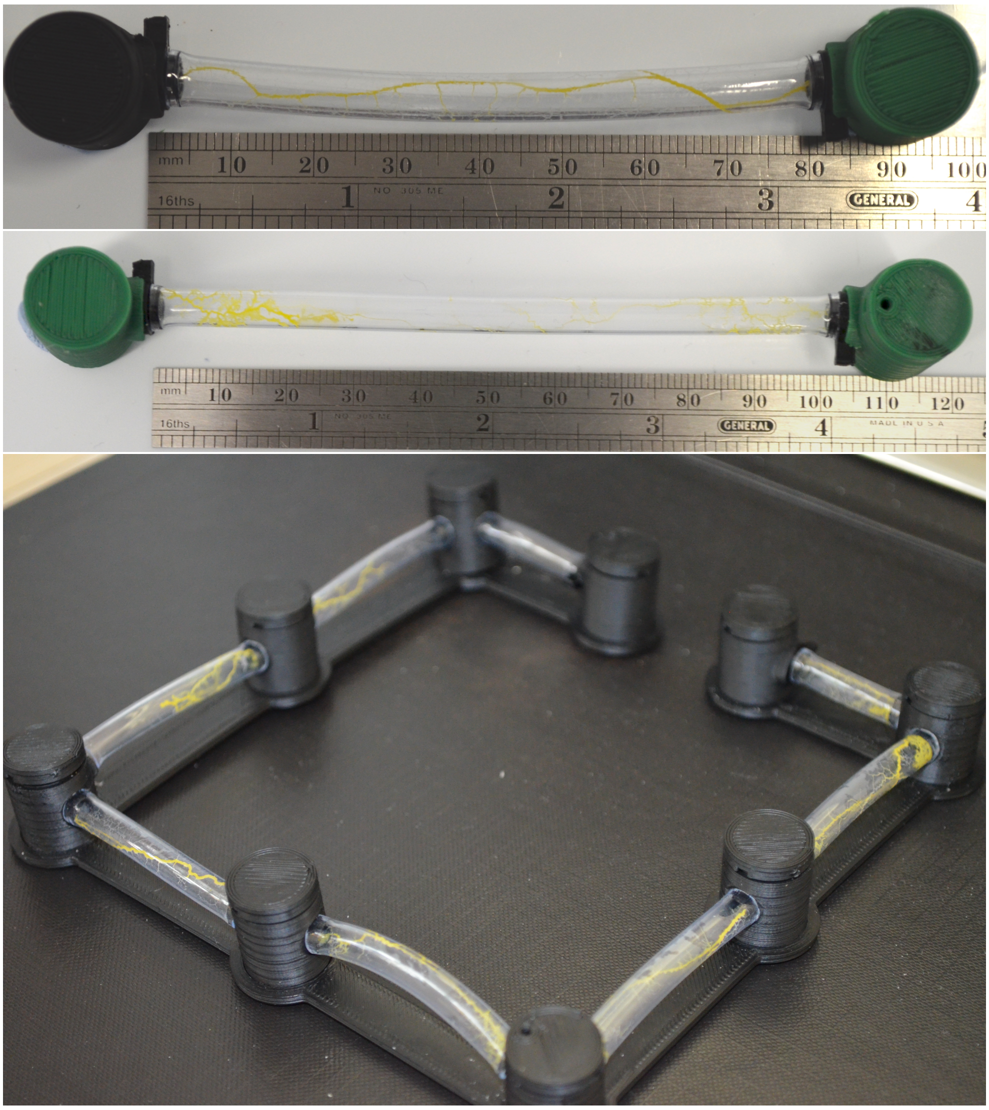


Figure 7.1: Photographs showing the receptacle being used to grow tubes at various lengths.

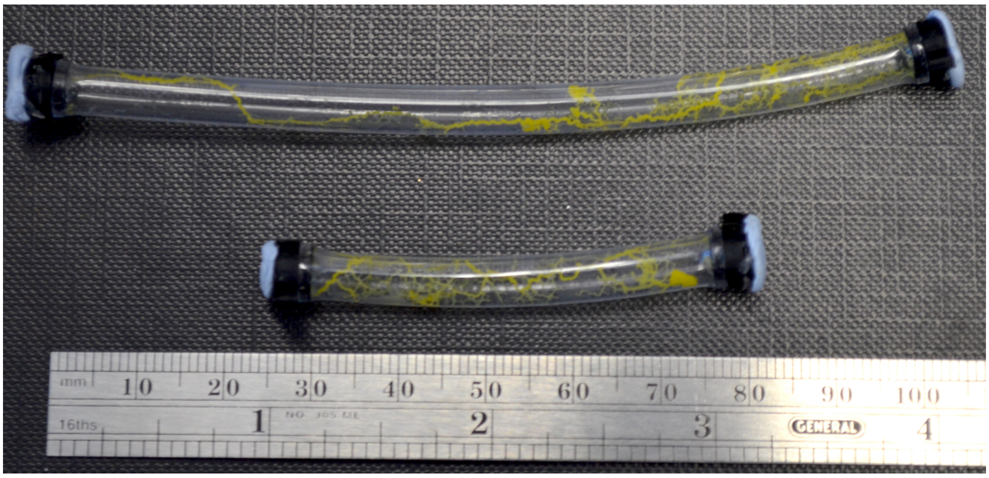


Figure 7.2: A photograph showing protoplasmic tubes that have been disconnected from the chambers.

to look at using biodegradable materials. This would allow for a completely environmentally friendly device to be implemented. Such a device could provide the wiring in events such as music festivals, where cables are often buried underground. Here, the environmentally friendly device could simply be left to biodegrade.

Suggested questions for future work to develop the receptacle:

- What are the electrical conductance properties of longer protoplasmic tubes?
- How can the receptacles be altered to allow for tubes to be clipped in and out?
- How can an environmentally friendly receptacle be realised?
- How can the receptacle be adapted to implement multicored *P. polycephalum* cables?

7.3.3 Musical Systems

As it currently stands, the final CM system presented in Chapter 6 relies on several large pieces of electrical equipment and a conventional computer (e.g. a laptop or desktop machine). Such a setup was useful during this research due to its versatility for prototyping. However, now that prototypes have been established, the next step is to develop a purpose-made device that is compact and cost-efficient. This could be achieved by replacing the electrical measurement equipment and conventional computer with microcontroller boards (e.g. Arduino or Raspberry Pi). As part of this process, it will be possible to address some of the system's limitations. For example, to increase processing speed, the new device will be able to address more than two memristors simultaneously. It should also be possible to integrate a larger total quantity of memristors, allowing for more sophisticated approaches to musical generation to be explored. For example, the system could respond to a pianist by processing their left hand and right hand independently, or it could generate responses for several different instruments at once. Moreover, networks of interacting memristors could be implemented in order to take better advantage of their 'brain-like' behaviour.

Aside from the music and memristor investigations, there are other avenues that may provide unique opportunities for real-time music technology. One feature of the plasmodium that researchers in UC have been able to harness in real-time is its shuttle streaming behaviour under a microscope, one example being logic gate schemes (126). Of course, exploiting this aspect of the organism requires a microscope and method of videoing-tracking. Therefore, it is likely that your average computer musician would not be able to investigate this avenue without investment or collaboration. Nonetheless, shuttle streaming may provide significant opportunities for implementing biological-based musical systems that can operate in real-time.

Mayne et al. have demonstrated that it is possible to load the organism with microparticles, which are picked up and moved around with shuttle streaming (241). The movement of these partials can be monitored under a microscope. Moreover, their motion can be altered: researchers have found that through gentle tactile stimulation of the protoplasmic tube, a person can change the direction and pause movement (see (242) for a video demonstration). It is possible that this stimulation method could be an approach for real-time interaction. Other researchers have discovered that the application of heat can significantly increase protoplasmic tube resistance (243). There is also a study that introduces methods for the selective functionalization of a protoplasmic tube with a conductive polymer, which allows for the rest of the organism's network to remain unfunctionalized and living (244). Such a method may provide means of developing a true hybrid piece of technology. Future research will investigate these UC progresses to review whether they can be used to implement real-time CM systems.

Suggested questions for future work into developing music technology with *P. polycephalum*:

- How can the musical systems presented in this thesis be rendered into a form that is not reliant on a desktop or laptop computer?
- Can real-time musical systems be developed using the organism's intracellular activity?
- How could the memristor's brain-like behaviour be used to develop intelligent musical systems?
- How can the plasmodium's intracellular behaviour be harnessed to implement CM systems?

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Appendix 1

8.1 Accompanying DVD