# THE SOUND OF THE HALLMARKS OF CANCER

by

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A portfolio of works and written commentary submitted to the University of Birmingham for the degree of

DOCTOR OF PHILOSOPHY

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September 2021

# ABSTRACT

The objective of this research is to create a mixed portfolio of data-driven composition and performance interfaces, fixed Electroacoustic/Computer music compositions, and live-improvised musical and audiovisual works reflecting cancer as a disease. The main methodology in generating the raw sonic material is the sonification of high-throughput, protein/RNA fold-change data, derived from the bio-molecular research of cancer cells. This data and relevant insight into the field are obtained as part of a collaboration with Barts Cancer Institute, in London, UK. Furthermore, for the purpose of musical effectiveness and reaching wider audiences, a focus has been placed on balancing the use of data-driven sonic material with composer-driven musical choices, by drawing upon the narrative of the *Hallmarks of Cancer* (Hanahan and Weinberg, 2011) which is a widely accepted conceptual framework in the field of cancer research for understanding the various biomolecular processes responsible for causing cancer. This method is adopted in order to inspire musical form, and guide some of the syntactic and aesthetic choices within both fixed and improvised works. In addition, this research also reflects upon the use of data sonification as an artistic tool and practice, while also addressing the contradictions and contention that arise as a result of scientific aims and expectations regarding sonification, resulting in a proposed original model for framing and classifying artistic works incorporating this approach.

# ACKNOWLEDGEMENTS

First and foremost, I would like to express my utmost gratitude to the Birmingham Electroacoustic Sound Theatre (BEAST), particularly my esteemed supervisors Dr. Annie Mahtani and Prof. Scott Wilson whose unending support, warmth and welcoming care throughout the past 4 years not only made this submission possible, but also inspired me and made me feel at home. I would also like to extend my sincere gratitude to Mr. Simon Smith whose kindness and giving knows no limits, and without whose all-encompassing support, I would not have been able to complete this project.

I would like to acknowledge and express my gratitude to Barts Cancer Institute, particularly Dr. Faraz Mardakheh, for collaborating on this project and providing me with data and valuable insight into the field of cancer research. I would also like to extend my sincere thanks to my talented and dear friend Ehsan Hemmati-Faräz for his hard work and contribution on the work, *Malignant Angiogenesis*.

I would like to express further gratitude to the Department of Music, particularly Prof. Matthew Riley, for their generous support of this project during difficult times. I am also deeply grateful to the College of Arts and Law for their generous granting of Music Scholarships which were crucial in the completion of this project.

Last but not least, I would like to thank my family for never stopping believing in me and for all the unconditional love and support they have and continue to give me during such turbulent and difficult times in our lives.

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# Chapter 1:

# DATA SONIFICATION

## 1.1 Introduction

The Sonification Handbook gives a clear definition for the term *Data Sonification* (Walker and Nees, 2011):

> An auditory display can be broadly defined as any display that uses sound to communicate information. Sonification has been defined as a subtype of auditory displays that use non-speech audio to represent information.

In other words (Kramer et al., 2010):

> Sonification is the transformation of data relations into perceived relations in an acoustic signal for the purposes of facilitating communication or interpretation.

Consider how an actual map is a two- or three- dimensional, visual representation of a geographical area, that also preserves the proportions of size and distance. Sonification is also a map of preserved proportions and data relations, but in the sonic realm rather than visual.

## 1.2 Sonification Approaches

**I - Auditory Icons & Earcons**

Auditory Icons are short communicative sounds that have a contextual and analogical relationship with the process or action they represent (Brazil and Fernström, 2011). In other words, it is as if the sound that you hear actually sounds similar or related to what it is meant to represent. For example, emptying the trash folder on your computer making the sound of crumpling up paper.

Earcons are sounds as symbols for actions or processes, not necessarily similar or related to the actions or processes they represent. For instance, the simple beeping of your phone when you receive a text message.

**II - Audification**

Audification is the most primary method of direct sonification, whereby waveforms are directly translated into sound (Dombois and Eckel, 2011). For example, seismic waves, traveling through the Earth's crust as a result of the vibrations of the tectonic plates over an extended period of time, have been audified so that we can hear actual earthquakes! This approach may require that the waveforms be frequency- or time-shifted [sped up or slowed down] into the range of waveforms which humans can hear.

**III - Parameter Mapping Sonification**

Parameter mapping sonification is the process of representing changes in one or many parameters of the data domain, with changes in one or many parameters in the sonic domain, in order to produce an inference-preserving sonification (Grond and Berger, 2011). For instance, mapping the water temperature in a kettle to the frequency, wave-form or any of the ADSR envelope parameters of a sound. According to Lily Asquith, parameter mapping encapsulates all of science and art in sonification. The science is in the rigorous mapping between the data and sound properties, and the art in where these relations are implemented. (Asquith, 2013)

**IV - Model-based Sonification**

While both Parameter-mapping and Model-based sonification approaches rely upon mapping different parameters from the data domain to the sonic domain in some respect, the latter (model-based sonification), focuses on generating sound via a physical or virtual model which is created and modeled on the data domain, as the user interacts with it (Hermann, 2011). In other words, creating a data-driven instrument that the user can play as they choose.

*Parameter Mapping*, and *Model-based Sonification* are the main technical approaches to data sonification adopted in this project. Both are incorporated in the design of interfaces used for composition and live performance (improvisation).

## 1.3 Functions of Sonification

Functions of Data sonification are indicated as below in the Handbook (Walker and Nees, 2011):

1. Alarms, alerts, and warnings

2. Status, process, and monitoring messages

3. Data exploration.

4. Art, entertainment, sports, and exercise.

A cursory review of the use of data sonification in the arts and entertainment, reveals an abundance of works which have made use of this method. Some examples of such works are indicated below:

- Iannis Xenakis' mapping of statistical and stochastic processes to sound in his *Metastasis* (1965) and other works (Capanna, 2001).
- John Dunn and Mary Anne Clarke composed the extended work called *"Life Music": The Sonification of Proteins*, in which different amino acid and protein folding patterns are mapped to pitch and instrumentation (Dunn and Clark, 1999).
- Frank Halbig's *Antarktika* translates ice-core data reflecting the climatic development of our planet into the score for a string quartet (Halbig, 2006).
- Carla Scaletti has sonified data from the ATLAS experiment at CERN and composed the dance work *QUANTUM* (Scaletti, 2013).

- Birmingham Ensemble for Electroacoustic Research (*BEER*) sonify data streams from the Large Hadron Collider at CERN, and use it as raw material for improvised live music and visualizations, in their *Dark Matter* Project (Wilson et al., 2020).

## 1.4 Scientific vs. Artistic Sonification

When it comes to Data Sonification, the purpose of the process noted in the Handbook is as follows (Walker and Nees, 2011):

> Sonification seeks to translate relationships in data or information into sound(s) that exploit the auditory perceptual abilities of human beings such that the data relationships are comprehensible.

Although comprehensibility and reproducibility are important factors under focus in data sonification as a scientific tool, when it comes to its use in music and the arts these may or need not be treated with the same level of priority. In other words, the differences in understanding, approaches, and aims in the use of data sonification as an artistic tool, as opposed to scientific, has led to a long lasting contention among scientific and artistic data sonifiers. The next section aims to tackle and shed some light on this issue.

# Chapter 2:

# A STRATA-BASED APPROACH TO DISCUSSING ARTISTIC SONIFICATION

"*What is the point of using data sonification in composition when the listener is not supposed to learn anything specific about the data itself through sound?"*

## 2.1 Introduction

Throughout my research, I have time and again encountered this recurring question from audiences and peers who listened to my work in concerts, or attended my talks. This question has indeed been a fundamental one of my own since the beginning of my PhD, which also reflects on my own mentality and aims in approaching data sonification and its use in my musical and compositional language. More importantly, the latter question points back to one of the long-lasting contentions in the discourse, highlighting the contradictions which arise between scientific and artistic expectations pertaining to sonification.

My answer has evolved throughout my PhD years, as has my compositional practice accordingly. In the beginning, I admittedly had a more stringent and puristic approach towards data, believing that my role as the composer was to simply observe, select and organize the sonified material into abstract works, thereby treating sonifications as concrete, indeterminate or 'found' sound (even though this description does not hold true in its entirety, as data sonification by definition encompasses, inter alia, sound synthesis, which is achieved through a consciously designed system, resulting from a combination of logical and aesthetic choices by the designer – and which can also be modified to a great extent.)

Having composed several pieces with this mindset, my intuitive and immediate justification at the time, was that I was, through sonification, preserving data relations in sound--data which originates from the same contextual origin as the narrative of the work in question, even though it may not necessarily correlate with it directly. Therefore I argued that both the identity and the musical intrigue and value of the final work was undoubtedly causally tied to the dataset as much as, if not more than, myself. Thus,

my use of data sonification added 'something' more to the piece which I could not. However, this justification did not seem to entirely convince either the more curious and inquisitive of listeners, nor myself. Therefore, I set out to examine existing works and conceptualize a more clear framework for artistic approaches and practices involving data sonification.

The culmination of this research is the following article which was conceived and co-authored with my supervisor Prof. Scott Wilson. The original manuscript was submitted to *Leonardo* journal and has been under consideration for publication.

## 2.2 The Strata Model

Much discussion of the use of data sonification for musical and artistic purposes focuses on seeming contradictions that arise from the ways in which this practice differs from and augments that of data sonification as a scientific tool. Over the past 30 years, this debate has become a rabbit hole of questions and arguments among scientists and musicians and composers, regarding the nature of music and sound-art and data sonification, and the extent of their relationships with one another.

A cursory review of data sonification in the artistic domain reveals an abundance of works, including musical compositions, performances, multimedia installations, etc. that have made use of sonification. As such it can be understood as both a tool and a practice. As mentioned, artistic use of sonification has given rise to contention regarding whether and how to delineate between the scientific and the artistic aspects of this practice, particularly in collaborations, and how and when they might overlap.

To address this, we have outlined three types of artistic sonification, which can serve as broad classifications. These are not orthogonal, but rather *cumulative*, and works can simultaneously employ characteristics of more than one. We propose a strata-based metaphor, in which each category rests upon and assumes the presence of the 'lower' ones. With that in mind, our identified layers are as follows:

1. Generative

2. Allusive

3. Curatorial

We discuss each in turn below. As noted, some of the works discussed will have aspects of more than one layer.

### 2.2.1 Generative

One attempt to resolve the difficulties in discussing artistic vs scientific sonification has been through alternate terminology, such as *Data Music* (Vickers, 2017) or *Data-driven Music* (Scaletti, 2018). This makes sense mainly insofar as it designates and validates the use of data sonification as a purely generative tool. Such uses fit within the definition of our lowest layer. Here, we will consider 'generative' as primarily connoting the intention to create novel musical or sonic material that might otherwise be difficult or impossible to create or arrive at manually. This includes results -- as a consequence --outside 'composerly' intention, or which embrace aspects of indeterminacy in their creation.

With *Generative* sonification, the context behind the data is not significant to the artist (or by extension perhaps the audience). The questions "what is the source data set?" and "why is the use of it particularly important?" are not matters of interest. The data is purely a means to an end and *can* in fact be completely random, manufactured, or invalid from a scientific standpoint. This is perhaps akin to some uses of serial and post-serial procedures in instrumental composition, or the use of chance procedures--both can involve the use of algorithmic techniques *without particular regard for the nature of the input or its context*. John Cage, György Ligeti, Per Nørgård, and others have employed different forms of algorithmic generation of musical events in their works, which could in some cases be understood as a *sort* of sonification using instrumental and vocal resources (Christensen, 2003). This analogy is not perfect however, since some such procedures have no input (which sonification has by definition), or have input that is strictly given in whole or part (e.g. the integers of Nørgård's Infinity Series). From a strictly technical standpoint, sonification does occur, but not as a result of direct mapping between the data domain and the sonic domain, or first-order sonification (to apply Scot Gresham-Lancaster's

terminology); and only as a secondary and more trivial means in the output--Gresham-Lancaster's 'second-order' sonification (Gresham-Lancaster, 2012).

It is worth noting that the use of the general term 'Data Sonification', without further explication, could appear as a sort of superficial 'label' that might add a false veneer of scientific gravitas to the work in question, which in other senses may well be a successful and effective musical composition (Vickers, 2017). One example might be Alvin Lucier's *Music for Solo Performer* (Lucier, 1965), which is often cited as one of the early examples of data sonification. In this case, alpha waves generated by Lucier's brain are captured using electrodes attached to his head, and sonified by electro-mechanically excited percussion instruments during the performance. The piece also draws on the guidance of the 'text-score', and the musical intuition of other musicians or performers involved (though 'for solo performer', sound is often freely routed by a second person). As Volker Straebel and Wilm Thoben point out:

> *Music for Solo Performer* is by no means a scientific setup where brain waves are automatically transformed into percussion sounds, but an artistic situation that asks for musically sensitive performers and assistants. The iconic image of a soloist performing motionlessly and relying only on brain waves to control percussion instruments is an artistic creation by the composer, not the technical reality of the piece (Straebel and Thoben, 2014).

Therefore, we can consider this work's use of data sonification as substantively *Generative*, insomuch as it is in essence a system for removing composerly control, intent, and expression in the manner typical of much post-Cageian experimental music, and not primarily 'about' brainwaves and their characteristics. We can also arguably consider an element of *Allusive* sonification here in addition to *Generative*, especially in terms of the reception of the work by the audience, if not the composer's focus. Though the piece is not 'about' brainwaves, its setup and performance do nevertheless draw the listener's attention to the role of alpha waves in its realization. We will discuss *Allusive* sonification in more detail in the next section.

### 2.2.2 Allusive

Moving past the *Generative* layer, we can now consider the possibility of a bridge between the two worlds of science and art. Such a bridge can function as a popularizing device that transforms complex, esoteric scientific information into a more accessible or artistic domain that appeals to sensory and emotional experience. This is perhaps what gives sonification its particular appeal, and may be why it has become a common tool in science-art collaborations. "When successful, a sonification in the form of abstract numeration creates something tangible, a direct experience of the sonification of that data*."* (Gresham-Lancaster, 2012). Alexandra Supper, who grounds her work in the concept of the aesthetic sublime, as discussed in the 18th century by Edmund Burke and Immanuel Kant, considers the aforementioned appeal as a result of the evocation of a sublime feeling or effect which can be attributed to some level of prior familiarity with, or knowledge of the science behind the data being sonified, i.e. the *auditory sublime* (Supper, 2013). Allusions to the Kantian sublime aside, we would argue that the sonification of abstract data, through its "tangible experience", creates a situation in which an empirically inconceivable phenomenon can become somehow more comprehensible, or at least 'experienceable' to the listener. This can arguably function like the application of reason through analogical means, aiding the understanding and experience of complex scientific phenomena by means of an alternate medium. Therefore, we can consider some prior knowledge of the source data and/or its context (or a way of acquiring it as part of the sonification experience, e.g. technical or programme notes) as crucial in achieving the aforementioned outcome. If such contextual information is absent, the resulting sonification will be experienced as arbitrary, or *Generative*.

*Allusive* sonification is predominantly an artistic tool, one used for creating pieces of music, as opposed to auditory displays, and thus does not aim to convey important information or salient aspects of the source data set through sound. In *Allusive* sonification, it is important that the audience understands the source of the data, even if it is not clear to them exactly how they are 'hearing' it. The resultant sound comes to connote the source of the data set, enriching the audience's experience through allusion to a

meaningful context. *Allusive* sonification may also entail consideration of the nature, meaning or context of the source data in making choices about mapping or other aspects of the realization.

Let's now consider some examples: Carla Scaletti used particle collision data from experiments conducted using the Large Hadron Collider (LHC) at CERN to compose electroacoustic music for a dance piece called *QUANTUM* (Scaletti, 2013). The work's inspiration and aesthetic directives derives from the data set used and its context. While the sound material is generated by mapping collision data parameters to sound synthesis parameters, certain compositional strategies, such as a circular panning gestures, immediately invoke a sense of 'spin' and 'acceleration' relevant to the LHC and particle collision experiments. 'What the piece is about' (its context) -- the significance of which is also reflected in the work's title -- is bound to what the data is 'about'. Other elements of the work, e.g. choreography, lighting and set-design, are also inspired by particle collision experiments (Vaghi, 2015).

Similarly, the *Dark Matter* project by the Birmingham Ensemble for Electroacoustic Research (BEER), uses particle collision data in improvised sonifications within the medium of Live-Coding (Wilson et al., 2020).The context of the underlying data has influenced both the sonification design and the utilization of material produced in the composition and performance of the work. One consideration that BEER has adopted is ignoring the order of collisions in the data they use, as subsequent collision events are unrelated, and their ordering--though perhaps tempting to reflect in music as a time-based art--is meaningless. This creates an element of flexibility that aligns with the improvisor's freedom of choice. More broadly, the LHC project serves as the primary inspiration for *Dark Matter*. It is *about* that in the same sense that music can allude to any subject through diverse means of explication, as well as implicitly through context. Metaphorically, the search for 'new physics' is mirrored in the performers' exploration of the musical potential of potentially vast data sets.

Here (in *Allusive* sonification), the various contextual and semantic concepts relating to the source data are *alluded* to in a composerly manner, making use of artistic tools such as abstraction, analogy or metaphor, dramatization, juxtaposition, superimposition, etc. in the process. The end result, as mentioned, is a work of art, not an auditory display. *Allusive* sonification can perhaps delineate where

both the practical and conceptual tools of music-making meet the intricacies and technicalities of the science, in an attempt to collaborate and bring into existence a novel artistic expression (strictly inspired by and about the science)--an artistic expression that carries with it additional conceptual weight, which is the result of the scientific domain being alluded to by the artist.

### 2.2.3 Curatorial

With *Curatorial* sonification, the goal is to accurately convey certain salient features of the data through sound to the listener in a meaningful way so that they are understood, i.e. to create auditory displays. Analogously to data visualization, such as a graph, the information represented is selected and focused upon by the designer, disregarding what may be uninteresting or considered as noise. It is then in a sense, *curated* to the viewer. The parameter-mapping sonifications of particle collision data produced by Lily Asquith at CERN (Asquith, 2013), or Mark Ballora's (et al.) numerous sonification projects, e.g. *Heart-rate data sonification* (Ballora et al., 2004) and *Sonification of web log data* (Ballora, 2010), can be named as a few examples of such an approach.

It is noteworthy that with *Curatorial* sonification, artistic design is still very much in play. This is reflected in the design of auditory displays which take into account certain aesthetic or musical considerations, not only to make the experience more sonically pleasant for practitioners, but more importantly to enhance communication, i.e. careful application of aesthetic choices can highlight the salient aspects of data or emphasize what is important about it to the audience. This characteristic can also be observed in data visualizations designed in a visually appealing manner while still being accurate and reliable. The many visualizations by David MacCandless at *informationisbeautiful.net* provide very good examples of the latter, in which design results in carefully curated, meaningful, and aesthetically pleasing presentations of complex information (McCandless, 2014). Aspects of this design serve to draw viewers' attention to important features by engaging with their imagination, aesthetic senses, and reason.

As for sonification, Asquith makes the claim (at least from a poietic point of view) that "parameter-mapping encapsulates all of science and art in sonification", i.e. the science is in the rigorous mapping

between the data and sound properties, and the art in where and how these mappings are implemented (Asquith, 2013). Similarly, Ballora describes how his design choices, e.g. using specific accented percussive sounds for the indication of chronology, in contrast with microtonal pitch for data values, are the result of both pragmatic and aesthetic considerations (Ballora, 2016). Such combination of scientific and artistic considerations points to the constructive dialogue between these two worlds, creating as a result, a vast space and potential for experimentation and exploration within the science-art polarity.

## 2.3 Conclusions and Implications

The 'strata' model presented herein has interesting implications for the collaborative process between artists and scientists, and can be useful in understanding and navigating some of the tensions that may arise from friction between the different motivations participants may have for undertaking such projects. Purely *Generative* sonification approaches seem likely to be 'one-way' collaborations, in that the artists will benefit from access to productive source material, but there is likely to be little or no benefit to the scientific project from which a piece derives. *Allusive* approaches bring us into the realm of outreach activities, possibly providing an aesthetic 'scaffold' upon which listeners may 'hang' their experience of the science--making it 'experienceable' through the evocation of Supper's *auditory sublime*. *Curatorial* works go still further into the realm of the pedagogical, potentially educating listeners about aspects of the science in addition to evoking an aesthetic response.

The three layers are differentiated based on the importance of the underlying data set and its context to the designer and the target audience, and how it is presented. A single work may be received on one or more of these levels, perhaps varying in different aspects of their realization. We have listed these strata below once more for clarity:

*1. Generative Sonification → primarily 'musical'; source of the data does not matter*

*2. Allusive Sonification → source of the data matters and is alluded to*

*3. Curatorial Sonification → more scientific; auditory display; conveys salient aspects of data*

Using the Strata metaphor, I can both broadly and specifically classify various aspects of my compositions in this portfolio, as well as the programming and patch work. These primarily fall within the *Allusive* layer, for most of the fixed composition works. There are also elements of *Generative* sonification, especially with regard to the live improvised performances and their respective interfaces. Furthermore, some of the sonification patches created, i.e. *the Data Handler*, *AddSynth* and the *Musical Model-based Sonification of Protein Fold-change Data* can be considered to encompass aspects of *Curatorial* sonification.

# Chapter 3:

# CONTEXT – THE HALLMARKS OF CANCER

## 3.1 Introduction

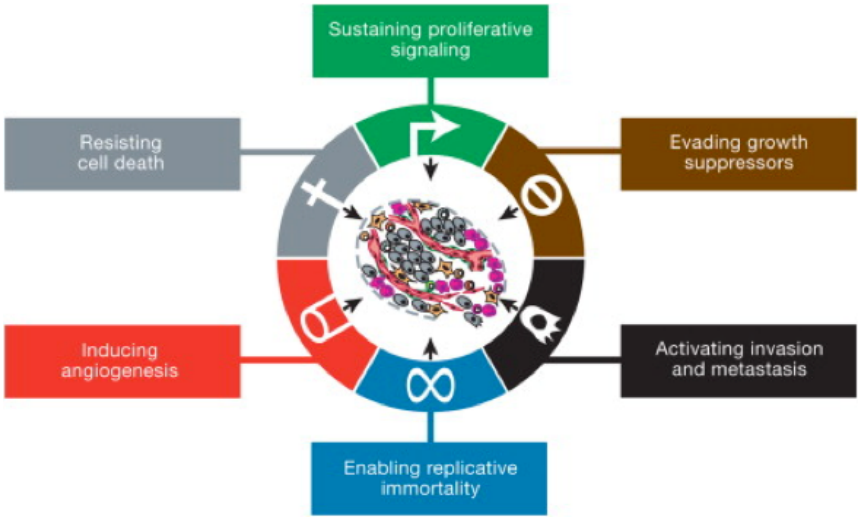



Figure 3. 1 – The Hallmarks of Cancer (Hanahan and Weinberg, 2011)

The Hallmarks of Cancer **(Figure 3. 1)** are characteristics that together constitute the capability of a normal cell to *evolve progressively* to a cancerous state. These biochemical traits provide a conceptual framework for better understanding various neoplastic diseases. The multistep process of human tumorigenesis could be rationalized by the necessity for early cancer cells to obtain these attributes which 'enable them to become tumorigenic and ultimately malignant' (Hanahan and Weinberg, 2011). These main hallmarks, explained briefly below, each inspire the musical narratives explored in terms of form and metaphorical sonic structures within each piece in this portfolio. These are explored further in the commentary of works that have been inspired by them.

**Sustaining proliferative signaling:**

This is the most fundamental trait of cancer cells which involves their ability to sustain chronic proliferation via keeping open the pathways for signals inducing this trait.

**Evading Growth Suppressors:**

Cancer cells must circumvent powerful programs that suppress cell growth and proliferation, many of which depend on the actions of tumor suppressor genes.

**Resisting Cell Death:**

The concept of programmed cell-death by apoptosis acts a natural barrier to tumorigenesis. Research has revealed that the apoptotic program is initiated in response to various physiological stresses which cells undergo, during tumorigenesis. Cancer cells develop various strategies to circumvent this barrier.

**Enabling Replicative Immortality:**

Most normal cell lineages in the human body are capable of only passing through a limited number of consecutive cell growth-and-division cycles, while it is widely believed that cancer cells require unlimited replicative potential in order to create clinically apparent tumors. This characteristic is known as immortalization.

**Inducing angiogenesis:**

Like normal tissues, tumors need nutrients and oxygen as well as means to evacuate metabolic wastes and carbon dioxide. The process of forming new blood vessels, sprouting from existing ones, is termed angiogenesis. During tumorigenesis, the switch for angiogenesis is almost always activated.

**Activating Invasion and Metastasis:**

Cancer cells in higher grades of malignancy invade local or distant tissue (metastasis). This results in cells' developing changes in their shape, and their form of attachment to other cells, and to the extracellular matrix.

## 3.2 The data and respective experiments at Barts Cancer Institute

A common trend in the majority of the hallmarks of cancer can be identified as an interplay of pro- and anti- regulatory proteins observed within cell samples (Hanahan and Weinberg, 2011). This enforces a concept of relativity which bears an important link to the data-model generated in the experiments run at Barts Cancer institute. This data-model and its value range are defined as binary logarithmic fold-change of proteins/RNA expression during the cells' transformation from normal to cancerous.

One of the key experiments conducted at Barts cancer institute which generates the aforementioned data-model, and which is also used in the sonification process, is the study of global Protein/RNA measurements and fluctuations, i.e. proteomics and transcriptomics analysis. These measurements are derived from cells that belong to a pancreatic cancer model in mice where the oncogene $KRAS^{G12D}$ - an oncogene which serves a vital role in tumor initiation and controlling tumor metabolism - can be switched on and off (Ying et al., 2012).

The *KRAS* gene facilitates the creation of a similarly named protein in the cell. This protein intercepts and transmits signals from outside of the cell to its nucleus which tell it to grow and multiply. When the *KRAS* gene mutates, its normal function becomes one of the most fundamental traits of tumorigenesis (Genetics Home Reference, 2015).

**Figure 3. 2** demonstrates a Mass Spectrometer (MS) device, which is used to extract the mentioned data. **Figure 3. 3** provides an example of this data, showing high-throughput, global, RNA fold-change measurements from a cell sample in which the *KRAS* oncogene has been switched on/off.


Figure 3. 2 – Mass Spectrometer at Barts Cancer Institute

| | A | B | C | D | E | F | G | H | I | J | |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | 12hrs_Log2(Oncogene OFF/ON) | 24hrs_Log2(Oncogene OFF/ON) | 36hrs_Log2(Oncogene OFF/ON) | 48hrs_Log2(Oncogene OFF/ON) | C: C: Keywords | C: C: KEGG name | C: C: GOCC name | C: C: GOMF name | C: C: GOBP name | C: C: Gene type | C: GSEA |
| 2 | 0.151547 | -1.10219 | 1.18763 | -0.86689 | 3D-structure;Cellcycle;Celldivision;Cellmembrane;Completeproteome;Cytoplasm;Cytoskeleton | Axon guidance;Chagas dise | cell part;centrosome;cyto | binding;catalytic activity;cati | biological regulation;cAM | protein_coding | ACEVEDO_LIVER_C |
| 3 | -0.0507698 | -1.2263 | 0.733113 | -0.468267 | Cellcycle;Celldivision;Completeproteome;DNAreplication;Nucleus;Phosphoprotein;Referencep | Cell cycle;Cell cycle - yeast | cell part;centrosome;chro | 3'-5' DNA helicase activity;bi | biological regulation;cell | protein_coding;protein_coding | ACTAYRNNNCCCR_ |
| 4 | -0.0627022 | 1.2203 | 1.3548 | 0.887139 | Completeproteome;Nucleus;Referencep roteome | | cell part;cytoskeletal part; | binding;lamin binding;protein binding | | protein_coding | ACAWYAAAG_UNK |
| 5 | 0.0158854 | -0.256123 | -0.835385 | -1.25104 | Cellmembrane;Completeproteome;Cytoplasm;Golgiapparatus;Membrane;Nucleus;Phosphopr | Bacterial invasion of epithe | acrosomal membrane;adh | binding;binding, bridging;DN | anatomical structure dev | protein_coding;protein_coding | AKT_UP.V1_DN.AK |
| 6 | -0.148351 | -0.241301 | 0.468242 | 0.0580604 | Completeproteome;Referencep roteome | | | binding;cation binding;ion binding;metal ion binding;n | protein_coding | | AACTTT_UNKNOW |
| 7 | 0.080265 | -0.790139 | 0.583954 | 0.0400841 | Alternativesplicing;Completeproteome;Developmentalprotein;Nucleus;Referencep roteome;Repeat;Repressor;Transcriptio | | cell part;chromocenter;chromosomal part;intracellular | anterior/posterior patter | protein_coding | AGTCAGC_MIR-345 | |
| 8 | 0.378796 | -0.35472 | 2.02235 | -0.0973704 | Acetylation;Completeproteome;Directproteinsequencing;Heme;Iron;Membrane;Metal-bindin | Alzheimer's disease;Cardiac | cell part;cytoplasmic part; | binding;catalytic activity;cation binding;cation transm | protein_coding | AAAGGGA_MIR-20- | |
| 9 | 0.105474 | 0.485986 | -0.330463 | -0.0719597 | Alternativesplicing;ATP-binding;Celljunction;Cellmembrane;Cellprojection;Coiledcoil;Completeproteome;Cytoplasm;Cytos | actin cytoskeleton;cell cor | adenyl nucleotide binding;ac | actin cytoskeleton organi | protein_coding | ATM_DN.V1_DN;B | |
| 10 | -0.328603 | -0.838825 | 0.169767 | 0.117093 | Acetylation;Alternativesplicing;Completeproteome;Cytoplasm;Nucleus;Phosphoprotein;Proteintransport;Referencep roteome | cell part;cytoplasm;intraci | protein transporter activity;t | establishment of localiza | protein_coding | ACOSTA_PROLIFER | |
| 11 | -0.162345 | 0.588433 | -1.26508 | -0.0670884 | | | | | protein_coding | | |
| 12 | 0.6496 | -1.35532 | 1.20024 | -0.361724 | 3D-structure;Completeproteome;GTP-binding;Lipoprotein;Magnesium;Membrane;Metal-bind | Long-term depression;MAP | adherens junction;anchor | binding;catalytic activity;cati | anatomical structure mo | protein_coding | BENPORATH_MYC |
| 13 | 0.135667 | -0.294527 | 0.777793 | -0.287145 | Acetylation;Acyltransferase;Carbohydratemetabolism;Completeproteome;Directproteinsequ | Citrate cycle (TCA cycle);Gly | cell part;cytoplasmic part; | acetyltransferase activity;cat | acetyl-CoA biosynthetic p | protein_coding | BLALOCK_ALZHEIN |
| 14 | 0.00852394 | 0.0690777 | -1.37771 | -0.997422 | Cellcycle;Celldivision;Completeproteome;Cyclin;Cytoplasm;Membrane;Nucleus;Referencepr | Cell cycle;Focal adhesion;Ja | cell part;chromatin;chrom | binding;enzyme binding;kina | biological regulation;cell | protein_coding;protein_coding;p | AAGCACT_MIR-520 |
| 15 | -0.33019 | 0.263254 | -0.65507 | 0.279181 | Completeproteome;Disulfidebond;Glycoprotein;Golgiapparatus;Membrane;Receptor;Referencep roteome;Signal;Transme | cell part;cytoplasmic part;Golgi apparatus;integral to membrane;intracellular me | | | protein_coding;protein_coding | BLALOCK_ALZHEIN | |
| 16 | -0.155891 | -0.571798 | 0.920372 | 0.056217 | 3D-structure;Acetylation;Antiviraldefense;Coiledcoil;Completeproteome;Cytoplasm;Immunity | RIG-I-like receptor signaling | cell part;cytoplasm;intraci | acid-amino acid ligase activit | biological regulation;cell | protein_coding | AGGGCAG_MIR-18 |
| 17 | 0.0489979 | -0.137122 | -0.347924 | -0.367267 | ATP-binding;Completeproteome;Cytoplasm;Kinase;Membrane;Metal-binding;Nucleotide-bind | Glycerolipid metabolism;Gl | cell part;cytoplasm;integr | adenyl nucleotide binding;ac | activation of protein kina | protein_coding | ADENYL_NUCLEOT |
| 18 | 0.204175 | 0.296564 | -0.151285 | 0.23688 | Carboxypeptidase;Completeproteome;Glycoprotein;Hydrolase;Protease;Referencep roteome;Secreted;Signal | | cell part;cytoplasmic part; | carboxypeptidase activity;ca | biological regulation;carb | protein_coding | BRUINS_UVC_RESI |
| 19 | 0.0585175 | -0.0408738 | -0.437968 | -0.11914 | Acetylation;Completeproteome;DNA-binding;Nucleus;Referencep roteome;Repressor;Transcription;Transcriptionregulatio | cell part;intracellular mer | binding;chromatin binding;C | aging;biological regulatio | protein_coding | AACWWCAANK_UI | |
| 20 | 0.263888 | -0.254895 | -0.10044 | -1.10024 | Acetylation;Completeproteome;Referencep roteome | | cell part;cytoplasmic part; | extracellular membrane-bounded organelle;extracellu | protein_coding | BASSO_B_LYMPHC | |
| 21 | 0.695579 | 0.316061 | 1.57901 | -0.401001 | Coiledcoil;Completeproteome;Phosphoprotein;Referencep roteome | | cell part;cytoplasm;cytopl | binding;identical protein bin | biological regulation;cell | protein_coding;protein_coding;p | AFFAR_YY1_TARGE |
| 22 | 0.128468 | 1.22568 | 1.42658 | 0.169749 | | | | | protein_coding | | |
| 23 | -0.0379977 | 1.12342 | 0.182591 | 0.10896 | Completeproteome;Metal-binding;Nucleus;Referencep roteome;Repeat;Zinc;Zinc-finger | | cell part;intracellular mer | binding;cation binding;DNA | biological regulation;neg | protein_coding;protein_coding | CAGCTG_VSAP4_C |
| 24 | 0.136327 | -0.384379 | -0.121689 | -0.131468 | 3D-structure;Alternativeinitiation;Catecholaminemetabolism;Cellmembrane;Completeproteor | Betalain biosynthesis;Stero | axon;cell body;cell part;cy | binding;catalytic activity;cati | alcohol catabolic process | protein_coding | BLALOCK_ALZHEIN |
| 25 | -0.12223 | 0.154906 | 0.668018 | -0.236094 | ATP-binding;Completeproteome;Ligase;Nucleotide-binding;Nucleus;Referencep roteome | | cell part;intracellular mer | adenyl nucleotide binding;ac | cellular macromolecule m | protein_coding | |
| 26 | -0.115316 | -0.631472 | 0.712198 | -1.14468 | Acetylation;Acyltransferase;Completeproteome;Lipoyl;Mitochondrion;Phosphoprotein;Refere | Valine, leucine and isoleuci | cell part;cytoplasmic part; | catalytic activity;dihydrolipoyllysine-residue (2-methyl | protein_coding | BURTON_ADIPOGE | |
| 27 | -0.00664616 | -0.317172 | 2.20142 | 0.121964 | Completeproteome;Cytoplasm;Nucleus;Referencep roteome;Ubl conjugation | | cell part;cytoplasm;intraci | binding;protein binding;protein domain specific bindi | protein_coding | AGCACTT_MIR-93_ | |
| 28 | -0.117013 | -0.25057 | 0.785932 | -0.246658 | Alternativesplicing;Cellcycle;Completeproteome;Cytoplasm;DNAdamage;Growthregulation;Initiationfactor;Phosphoprotei | cell part;cytoplasm;intraci | binding;nucleic acid binding; | biological regulation;bios | protein_coding | ACEVEDO_LIVER_C | |
| 29 | -0.189274 | -0.359504 | -0.882882 | 0.1949 | | | | | protein_coding | | |
| 30 | -0.160344 | -0.835943 | -0.76269 | -0.178301 | Alternativesplicing;Completeproteome;Cytoplasm;Phosphoprotein;Referencep roteome | | cell part;cytoplasm;intracellular part;macromolecular c | anatomical structure dev | protein_coding | ACEVEDO_FGFR1_ | |
| 31 | -0.240268 | 0.337905 | -2.58043 | -0.440268 | Alternativesplicing;Completeproteome;Referencep roteome | | cell part;cytoplasmic part; | catalytic activity;kinase activ | cellular metabolic proces | protein_coding | CAIRO_HEPATOBL |
| 32 | 0.526979 | 0.985415 | 2.19283 | -0.7518 | Autocatalyticcleavage;Cellmembrane;Completeproteome;Disulfidebond;Glycoprotein;Hydrolase;Membrane;Protease;Ref | cell part;extracellular mer | cargo receptor activity;catab | biological regulation;mac | protein_coding | ATM_DN.V1_DN;B | |
| 33 | -0.0325232 | 0.0655177 | 0.985864 | 0.292907 | Acetylation;Completeproteome;Directproteinsequencing;Electrontransport;FAD;Flavoprotein; | Alzheimer's disease;Huntin | cell part;cytoplasmic part; | binding;catalytic activity;NADH dehydrogenase activit | protein_coding | BHATI_G2M_ARRE | |
| 34 | 0.107754 | -0.0977414 | 0.100401 | -0.706047 | 3D-structure;Completeproteome;Disulfidebond;Glycoprotein;Glycosyltransferase;Golgiappara | Mucin type O-Glycan biosy | cell part;cytoplasmic part; | acetylgalactosaminyltransfer | carbohydrate metabolic | protein_coding | ACAGGGT_MIR-10 |
| 35 | 0.137733 | -0.0278935 | -0.678072 | -0.357554 | Completeproteome;Ligase;Metal-binding;Phosphoprotein;Referencep roteome;Repeat;Ubl conjugation pathway;Zinc;Zinc-f | cell part;intracellular | binding;catalytic activity;cati | cellular macromolecule m | protein_coding | ACEVEDO_LIVER_C | |
| 36 | 1.07082 | -0.0375762 | -1.29546 | -2.25566 | Completeproteome;DNA-binding;Metal-binding;Nucleus;Proteomicsidentification;Receptor;Re | Huntington's disease;Osteo | cell part;cytoplasmic part; | actinin binding;activating tra | activation of caspase acti | protein_coding;protein_coding | ACTGTGA_MIR-27 |
| 37 | 0.667746 | -1.07417 | 0.289506 | -0.355294 | Alternativesplicing;ATP-binding;Cellmembrane;Completeproteome;Cytoplasm;Kinase;Membr | Acute myeloid leukemia;B | cell part;cell projection;cy | adenyl nucleotide binding;ac | activation of MAPKK acti | protein_coding | APOPTOSIS_GO;BA |
| 38 | 2.02071 | -1.70563 | 4.17403 | -1.23315 | | | | | protein_coding | | |
| 39 | -0.411511 | 0.0582626 | -0.130119 | -0.212466 | Cellmembrane;Completeproteome;Cytoplasm;Membrane;Phosphoprotein;Referencep roteome | | cell part;cytoplasm;intracellular organelle part;intracel | biological regulation;cell | protein_coding | CCAGGGG_MIR-33 | |
| 40 | 0.239131 | -0.670519 | 1.0902 | -0.747005 | ATP-binding;Cellmembrane;Completeproteome;Glycoprotein;Kinase;Magnesium;Manganese;( | Cytokine-cytokine receptor | activin receptor complex;c | activin binding;activin recep | activin receptor signaling | protein_coding;protein_coding | AACTGGA_MIR-145 |
| 41 | 0.0929279 | 0.634883 | 0.468354 | 0.222794 | Acetylation;Alternativesplicing;Completeproteome;Phosphoprotein;Proteintransport;Referencep roteome;Transport | | cell part;extracellular membrane-bounded organelle;ex | biological regulation;cell | protein_coding | AACTTT_UNKNOW | |
| 42 | 0.00370169 | 1.90102 | -1.1598 | 0.457361 | Alternativeinitiation;Alternativesplicing;Cellcycle;Cellprojection;Completeproteome;Cytoplasm;DNAdamage;Metal-bindi | cell body;cell part;cell pro | binding;cation binding;ion bi | anatomical structure dev | protein_coding | AAGCAAT_MIR-137 | |
| 43 | 0.434491 | -1.40969 | 0.42296 | -0.853615 | Completeproteome;Cytoplasm;Nucleus;Phosphoprotein;Referencep roteome;Repeat;WDrepeat | | cell part;cytoplasm;cytopl | ligand-dependent nuclear re | biological regulation;cell | protein_coding | BASAKI_YBX1_TAR |
| 44 | 0.143215 | -0.574416 | 1.72679 | -0.252484 | Acetylation;CF(0);Completeproteome;Directproteinsequencing;Hydrogenintransport;Iontran | Alzheimer's disease;Huntin | cell part;cytoplasmic part; | ATPase activity;catalytic acti | anatomical structure dev | protein_coding;protein_coding | ASTON_MAJOR_DI |
| 45 | 0.113359 | -0.10482 | 1.00222 | -0.711829 | Completeproteome;DNA-binding;Nucleus;Referencep roteome;Transcription;Transcriptionregulation | | cell part;intracellular mer | beta-catenin binding;bindi | anatomical structure dev | protein_coding | AACTGGA_MIR-145 |
| 46 | -0.00590897 | -0.0483921 | -0.826602 | -0.406587 | Acetylation;Alternativesplicing;Biologicalrhythms;Completeproteome;Cytoplasm;Directproteinsequencing;DNA-binding;M | cell part;cytoplasm;extrac | binding;DNA binding;nucleic | biological regulation;bios | protein_coding;protein_coding;p | AGTTCTC_MIR-146 | |
| 47 | 0.39385 | -0.345288 | 1.32622 | -0.516248 | Apoptosis;Completeproteome;Cytoplasm;DNA-binding;Nucleus;Phosphoprotein;Referencep roteome;RNA degradation | | cell part;cytoplasm;intraci | binding;DNA binding;ligand- | apoptosis;biological regu | protein_coding | chr2p13;COLL1S_PI |
| 48 | -0.0594454 | 0.725937 | 1.10309 | 0.624157 | 3D-structure;Completeproteome;Disulfidebond;Glycoprotein;Hydrolase;Lipidmetabolism;Lyso | Lysosome | apical cortex;cell cortex pa | beta-N-acetylgalactosaminid | behavior;biological regul | protein_coding;protein_coding | AMIT_SERUM_RES |
| 49 | 0.271869 | -0.089196 | 0.653254 | 0.214982 | Alternativesplicing;Angiogenesis;ANKrepeat;Celljunction;Cellmembrane;Completeproteome;Cytoplasm;Cytoskeleton;Men | cell junction;cell part;cell- | binding;cytoskeletal protein | anatomical structure forr | protein_coding;protein_coding | AACTTT_UNKNOW | |
| 50 | 0.299589 | -0.216085 | 1.07288 | 0.800627 | Antiport;ATP-binding;CBSdomain;Chloride;Completeproteome;Endosome;Iontransport;Membrane;Nucleotide-binding;Re | cell part;cytoplasmic part; | active transmembrane transporter activity;adenyl nuc | protein_coding;protein_coding | ANION_CHANNEL_ | | |
| 51 | -0.347636 | -0.243635 | -0.793483 | -0.722942 | Allostericenzyme;ATP-binding;Completeproteome;Glycolysis;Kinase;Nucleotide-binding;Refern | Amino sugar and nucleotid | cell part;cytoplasmic part; | adenyl nucleotide binding;ac | alcohol catabolic process | protein_coding | ABBUD_LIF_SIGNA |
| 52 | -0.175481 | 0.428727 | -1.75582 | 0.219704 | Alternativesplicing;ATP-binding;Coiledcoil;Completeproteome;Cytoplasm;Cytoskeleton;Golgiapparatus;Motorprotein;Myc | actomyosin;brush border; | actin binding;actin filament | actin cytoskeleton organi | protein_coding;protein_coding | AAAYRNCTG_UNKI | |

12-48hrs Oncogene removal | Keywords | GSEA | KEGG_name | 12 hrs | 24 hrs | 36 hrs | 48 hrs | +

Figure 3. 3 – 12-48hrs Oncogene Removal Experiment Protein Fold-change Data

In addition to the protein/RNA measurement values, there are expanded, identifying categories which give accounts of each measured protein/RNA's recorded biological functions, chromosomal location and regulation within external databases such as GSEA (*Gene Set Enrichment Analysis)*, KEGG (*Kyoto Encyclopedia of Genes and Genomes)* and keywords relating to the function(s) of specific proteins/genes.

### 3.2.1 Approaches to Data in the Sonification Design

While having an allusive approach to the utilization of the sonified material in the composition of the works in this portfolio eliminated the strict need for comprehensibility and extracting meaningful sonifications of the high-throughput protein/RNA fold-change data (or a *Curatorial* sonification), my experimentation with this particular dataset and the approaches I chose to adopt in designing sonification systems were in fact informed by the characteristics and semantics specific to it. These approaches are outlined and described below. In line with Alberto de Campo's *Sonification Design Space Map* concept (SDSM), various generalizable principles in terms of the resulting data processes for each approach are also highlighted (de Campo, 2007).

**Column-based** (statistical analysis data for protein/RNA activity over each discrete time period)

The first approach to the data was a column-based traverse and sonification of the high-throughput dataset. This is essentially a vertical traverse of various fold-change values pertaining to a specific time frame (column) of the data, which is implemented in the operation of the *Data Handler* and *AddSynth* patches. Each stream of fold-change values for each column is mapped to and modulates a continuous FM signal, which is layered under similar streams resulting from other columns.

The resulting streams exclude the time-based evolution of proteins/RNAs' fold-change values, but instead yield statistical analysis of the global protein/RNA fold-change within each time frame, similar to a histogram. This is done via the counting of passing fold-change data which fall into concentric categorized value ranges. These ranges are essentially significance groups labeled from *Least Significant* (Log2 values within the range [-1, 1], meaning protein/RNA expression has decreased to more than half or increased to less than double of that protein/RNA's original level), to *Most Significant* (Log2 values **outside** the range [-2.5, 2.5], meaning expression has decreased to more than approx. one tenth or increased to more than five times of that protein/RNA's original value). The *weight* of each category is the number of proteins/RNAs which fall within it, and is mapped to FM synthesis base signal waveform, i.e. the more significant proteins/RNAs produce harsher tones (sawtooth/triangle), and less significant

groups produce smoother ones such as sine waves. More details regarding the implementation of this operation in the patch work can be found in Chapter 5 and Appendix A.

From the perspective of de Campo's SDSM and generalizable principles, the continuous sonification of each column produces *Continuous Data Representation*. The vertical traverse reduces the number of data dimensions, while increasing the throughput of data points. However, the extrapolation of statistical data can be considered a secondary, added dimension. In addition, the operation of *AddSynth* utilizes multiple simultaneous sonifications of each data column which are layered on one another, and therefore increase the number of parallel sonification streams (de Campo, 2007).

**Row-based** (vectorial evolution of each protein/RNA fold-change over the course of the experiment)

This method functions perpendicular to the previous one. Instead of a continuous sonification stream of protein/RNA fold-change values within one time frame, the result is the sonification of each protein/RNA as a discrete data point, which evolves over the time-span of the experiment scaled from hours down to seconds.

This approach is implemented in the operation of the *Modified Data-driven cataRT* and the *Data-driven Ambisonic Spatializer and Make noise Modular-Synth Modulator*, where the primary focus is the mapping of protein/RNA fold-change data vectors into modifiable sonic and spatial gestural trajectories, e.g. control voltage curves for synthesis modulation, or the position of sound sources within the virtual space in higher-order Ambisonics. For more technical details regarding the implementation of the latter patches, please refer to Chapters 5 and 15.

The *Data-driven MIDI VST Synth* employs a similar row-based approach. However, instead of discrete data vectors, protein/RNA fold-change values are continuously mapped to MIDI events. This continuous mapping removes the temporal evolution of values (i.e. their vectorial characteristic). More details on the implementation of this can be found in Chapter 10.

Based on SDSM, with the *Modified Data-driven cataRT* and the *Data-driven Ambisonic Spatializer and Make noise Modular-Synth Modulator*, the focus on the sonification of data vectors as discrete data

points, reduces the overall data throughput in the sonification, while increasing the number of data dimensions. Moreover, one common data analysis strategy implemented in this approach, and in all of the subsequent patches, is the calculation and use of the central tendency of each protein/RNA's fold-change values, as part of the sonification. Similar to the previous approach, the central tendency can be considered as a secondary added data dimension (de Campo, 2007).

**Search-based** (cross-referencing of *Category Enrichment* data and global protein/RNA fold-change data)

Implemented as a secondary functionality of the *Data Handler*'s operation, the search-based approach essentially facilitates an interjection of the row-based approach within the column-based one. This is done so via the *Category Matching Module*, which uses an additional data set referred to as *Category Enrichment Data*. The latter provides statistical data pertaining to specific measured proteins/RNAs in the same experiment, e.g. their population size (N), Z-score, P value, Mean, etc. as well as their 'names' within identifying categories mentioned earlier, e.g. GSEA, KEGG, Keywords, etc. and is used as a means to extract significant proteins/RNAs out of the global measurements. This data set works as a key to the search function which cross-references the global protein/RNA fold-change measurements in a time-based manner. When there is a match, the continuous sonification streams of various columns are replaced with the static sonification of the matched protein/RNA. Further technical details on the implementation of this data set and the *Category Matching Module* can be found in Appendix A.

From the SDSM perspective, the matching reduces the data throughput, while increasing the number of data dimensions used in the sonification. The latter also reduces the number of parallel streams down to one for the matched protein/RNA (de Campo, 2007).

**Model-based** (Hierarchical clustering of vectorial data for a limited number of proteins)

This approach is explored and implemented in the design of the *Musical Model-based Sonification of Protein Fold-change Data* interface*,* which is elaborated in Chapter 11 and Appendix B. One of the inspirations for the design of the latter interface was the hierarchical clustering of global protein/RNA

fold-change data set, which is a common practice among cancer researchers to reduce the high-dimensionality of the latter data.

The implementation of this method includes the dispersion of data vectors as fixed points in the virtual 3D space, which in turn interact with a dynamic virtual mass-spring model, mediating between the data space and the sonification space in order to produce sounds. The mass-spring model produces 80 parallel streams of discrete sonifications on separate audio channels, each of which is modulated by the fold-change values of one measured protein/RNA.

According to SDSM, the hierarchical clustering of data vectors reduces the number of data dimensions. However, the inclusion of the dynamic, physical model, introduces new, secondary physical data dimensions into the sonification, e.g. velocity of the masses or their distance from the fixed, clustered data points. Moreover, having discrete-point sonifications of a limited number of proteins reduces data throughput. However, the 80 simultaneous sonifications on separate channels sees an increase in the number of parallel sonification streams (de Campo, 2007).

# Chapter 4:

# COMPOSITIONAL PROCESS

## 4.1 Background

Many of the influences governing my compositional and musical language acquired in my journey in music so far stem from the years I wrote and played Alternative/Nu-Metal music with my band in Tehran. Considering that is when I actually began writing music as a teenager, much of the emotional and expressive content driving the pieces forward has always been underlined by a constant feeling of oppression and restrictions. For the most part, I believe this is caused by the oppressive Iranian regime, having subjected its people, specifically those in the creative sector, to an almost relentless abuse, prosecution and punishment for creating any art that even in the most abstract way voices protest, throughout the past 40 years. Out of this subconscious and subliminal battle of, I dare to say, almost every young Iranian musician living and trying to work in Iran, came an utter fascination with grotesque and avant-garde music on my part. While this began with writing and playing Rock and Metal music within the popular music sphere, I believe that it is one of the most fundamental forces guiding my interests as a composer to this day.

Expanding this to a broader outlook on my work in this particular moment, my ears have always demanded a 'shock factor'. This shock factor has rarely fitted within the general definition of 'beauty' from a romantic or post-romantic aesthetic perspective, if not opposing it in a literal and intentionally obvious way. With my instrumental music this has pushed me towards utilizing melancholic and suspended harmonies juxtaposed with sharply-accented dissonant chords, as well as a broad tendency towards rhythmic fluidity and complexity. At its core, the duality that resides deep in the sonic fabric of music--tension and release--is mostly present and emphasized in an exaggerated manner in my music, feeding into and highlighting the seemingly ever-expanding divide between identity and ideology, peace and turmoil, acceptance and alienation, etc.

With electroacoustic composition, which more often than not dismisses the basic concepts of rhythm, pitch, harmony, etc. present in conventional instrumental music, this fundamental drive still persists and remains heavily dominant, resulting in a leaning towards abrasive textures, busy and 'noisy' sound-worlds, abrupt transformations, and accented beats that paint the unexpected shattering of the illusion of stability within a section. I believe these more or less preserve that same conceptual approach towards writing music, satisfying the need for some semblance of the unexpected--'the shock factor'.

When I began writing music about cancer, I started looking at it through the scope of my own experience and background. Broadly speaking, to me cancer became the oppressor, the usurper--that powerful invisible force that wreaks havoc on the microscopic and subsequently macroscopic levels--the disease which still to this day, with all the valuable scientific and medical advances made, cunningly evades humanity's efforts to eradicate it. In other words, analogically cancer became the grotesque conceptual embodiment that in many ways reminded me of the oppressive Iranian regime, and that in return, meant cancer research was the sole force of resistance, leading the fight against it. This analogy dominates my work in this portfolio and broadly justifies the use of grotesque and abrasive sonic material in the weird and eerie compositions which reflect this violent and deadly ailment. Where there is any sense of optimism conveyed through the music, it points to the scientific effort in this battle, and remains in constant struggle and tension with the dominating dark and grotesque elements.

When it comes to existing repertoire of DNA/Protein sonification music composed in the nineties, despite each work having unique compositional characteristics and processes, there seems to be present a common trend of pitch/rhythm-based mappings to the comprising Amino Acids, in some cases contained within established musical ethnicities, moods and genres. Works such as M. A Clark's and John Dunn's *Life Music* (Dunn and Clark, 1999), Susan Alexjander's *Sequencia* (Alexjander, 1994) or David Deamer's *DNA Suite* (Deamer and McLaughlin, 1990) tend to rely on pitch/rhythm-based, instrumental music. In this project however, in line with the overall leaning towards the use of grotesque sonic material, a more open, noise-based approach towards the sonification of such data is adopted to create a wider range of produced sonorities and do away with the limitations of adhering to any specific musical genre.

## 4.2 Patchwork and composition/improvisation

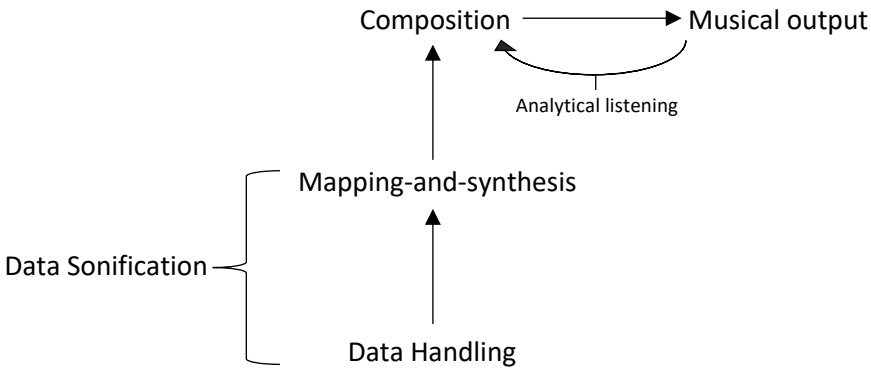



Figure 4. 1 – Programming and (Fixed) Composition Diagram

The sonification process and its implementation in MAX/MSP programming environment comprises of multiple patches which can be divided into three main levels in terms of functionality. First is the *data-handling* level, which bears the tasks of inputting, parsing and categorical processing of the data, in a time-based manner. The reason for this design choice is to give the sonification events the same time-based characteristic of musical events in a piece of music. The second level is the *mapping-and-synthesis* level whose task is to map data values to multiple sonic (and rhythmic) parameters and generate sounds using multiple synthesis techniques. This stage consists of multiple experimental sound synthesis modules, each of which contain different mapping algorithms based on their mode of function and approach towards synthesis. These include FM and Experimental Synthesis, Granular Synthesis (through Model-based Sonification) and Concatenative Synthesis. At the top level of the compositional process, these modules are often used simultaneously and in conjunction with one another to produce varied sonorities and colors.

Finally, on the third level, the generated sounds are then selected and organized to form musical compositions directed by the narrative of the hallmarks of cancer. This last level is only considered as a separate and independent stage with regard to fixed compositions, as in that scenario, there is opportunity for processing and editing of sonified material. Later patches developed in this project have a particular focus on live improvisation and performance as their primary function. In fact, the transient

nature of improvisation and the challenge of lacking retrospective, analytical inspection and manipulation of the sonified material changes the **Figure 4. 1** diagram, as well as naturally demanding a wider range of real-time control of the mapping ranges and synthesis parameters from the user while carrying out the sonification. In other words, instead of treating the sonified material as raw concrete sounds to be manipulated and collaged together into an abstract piece, the focus shifts towards the modification of the sonification process itself in real-time using imposed compositional directives as part of the improvisation process. These directives are inspired or influenced by concepts relating to the broader context of the work, and can be exemplified as overall trajectories for the movement and development of masses or shapes of sound, overall form of the work, overall choice of textures, etc. **Figure 4. 2** demonstrates the relationship between the data sonification task and improvisation.

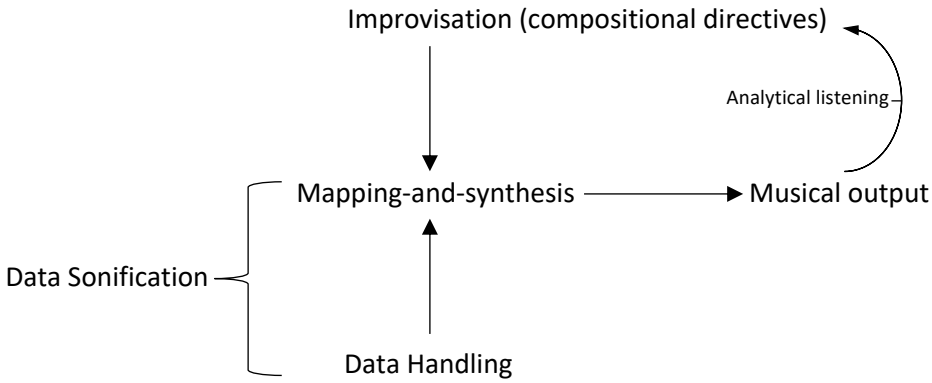



Figure 4. 4– Programming and (Live) Improvisation Diagram

The overall mode of the programming design is also inspired by the datatype being enormous, high-throughput global measurements, i.e. measurements of every protein/RNA that there is and can be measured in the sample. Analogously, I have always pictured it as swarm or a backdrop of chatter or noise coming from the cell sample, some of which may be chatter belonging to biochemical culprits of cancer.

# Chapter 5:

# THREE SONIFICATION PATCHES

This chapter features brief descriptions of a series of sonification Max patches created and utilized for the composition of a number of fixed pieces whose commentaries can be found in the following Chapters 6 – 9.

## 5.1 The Data-handling Component (Data Handler)

The data-handling component was the first patch created in this project. As apparent from its title, it bears the task of inputting, storing, parsing and traversing the source data in a time-based manner, and sending data values and relevant additional information for the mapping and synthesis stage. **Figure 5. 1** shows Data Handler's GUI below.

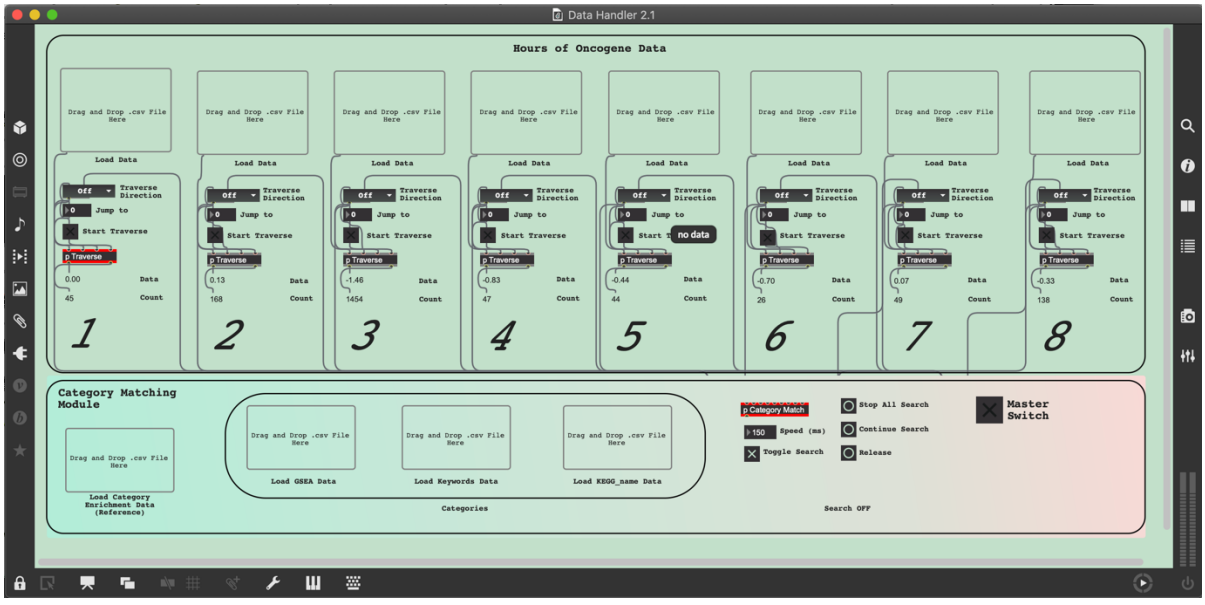



Figure 5. 1 – Data Handler GUI

### 5.1.1 Data Traverse

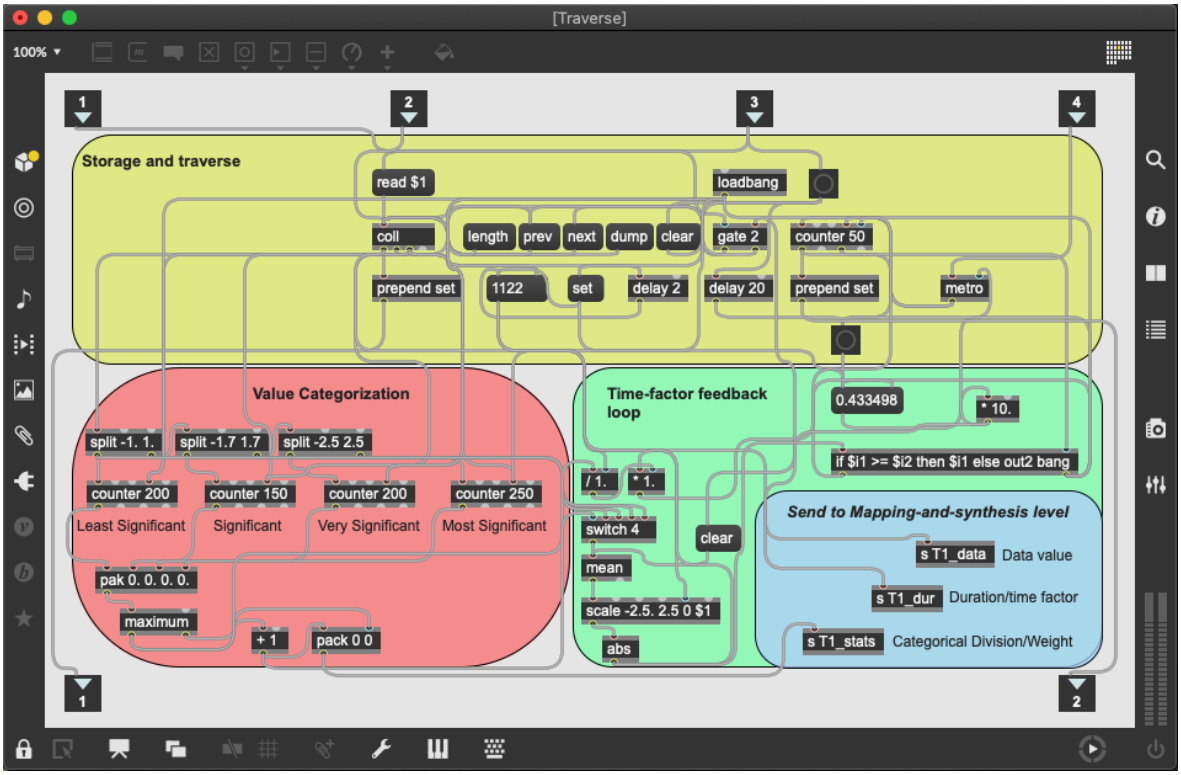



Figure 5. 2 – Data Traverse Module

*Data Traverse* is the main engine of the data-handling component. As shown in **Figure 5. 1**, There are eight identical instances of the traverse sub-patch, each designated to a specific time-frame of the proteomics and transcriptomics analysis experiment. Once the data is loaded and the patch is operational, each Protein/RNA value of each time-frame is traversed with a time-factor (speed of data traverse) which is also dynamically decided by the data using a feedback loop.

To allow the inference of meaning from the data in the mapping process, Protein/RNA values within each time-frame are categorized into four groups, *Least Significant, Significant, Very Significant, Most Significant.* This is the core level of processing and parsing of the data values (**Figure 5. 2**). In addition, the weight of each group is calculated using counters, determining which category-group is dominant at each moment of the data traverse within each time frame. The data is then sent to the *mapping-and-synthesis* level, wrapped up in a threefold package: Data Values, Duration/time factor and Categorical

Division/Weight. More technical information regarding other modules and aspects of *Data Handler*'s operation is included in the appendix.

## 5.2 AddSynth

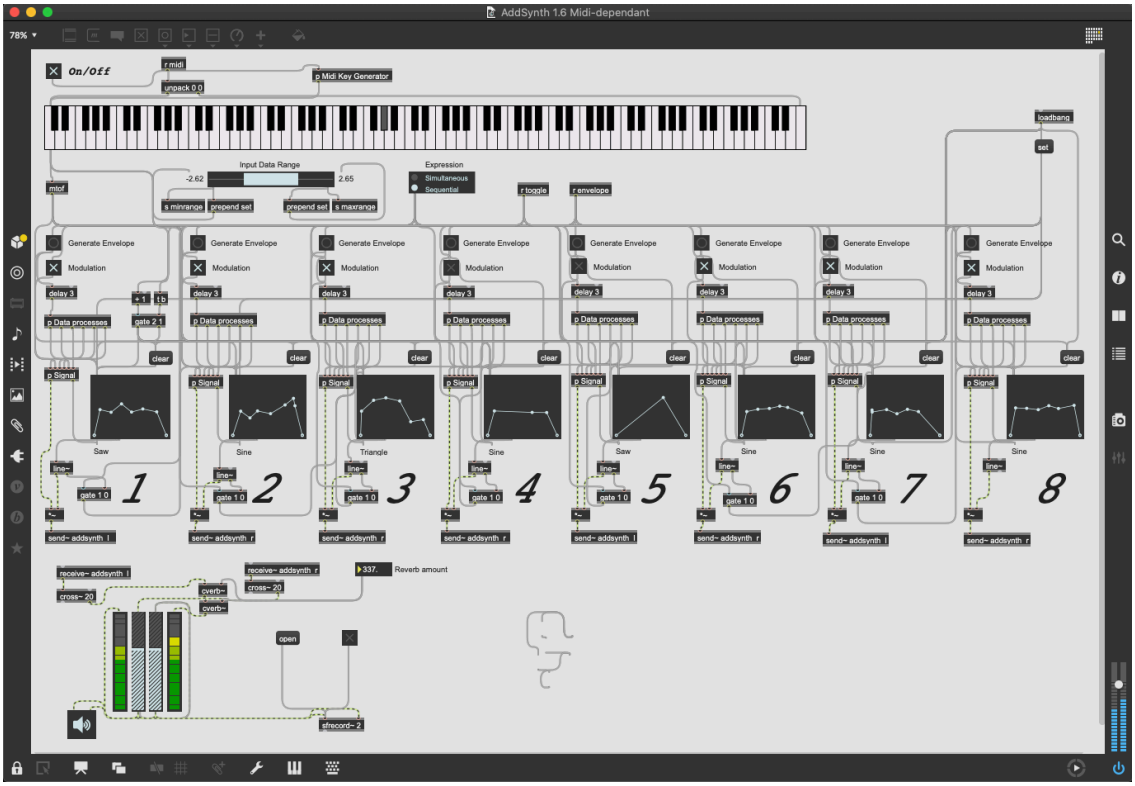



Figure 5. 3 – AddSynth GUI

This patch operates as one of the primary synthesis tools in generating sound in this level. As it can be seen in **Figure 5. 3**, it consists of the same column-based structure seen in *Data Handler* and is designed based on the layering principle of additive synthesis.

Each column (or time-span) of the experiment produces one layer of data-driven synthesized tone. These are then combined and layered onto one another (additive synthesis), and sent to alternating left and right channels.

The GUI provides basic control over generating data-driven envelop points and toggling on/off the signal modulation, for each layer of sonified tones. The generated envelopes can also be manually modified by clicking on the function displays. In addition, the user can also modify and control global parameters

affecting all layers. These parameters are the volume level, the input data range in the mappings, expression (i.e. playback mode of each layer), adding a simple reverb to the output and recording it. *AddSynth* also has the capability of being played like a standard synthesizer using any external Keyboard-based MIDI interface. More technical information regarding this patch can be found in the appendix section.

## 5.3 Modified, Data-driven cataRT (Concatenative Synthesizer)

This patch was created as a minor modification to IRCAM's cataRT, which produces concatenative synthesis of a corpus of sound grains, organized based on various sonic parameters (Schwarz et al., 2006). The primary goal of this modification was to achieve data-driven control of cataRT, for **live performance**, at its highest level of operation, i.e. the user's interaction with the synthesizer, as opposed to the lower-level spectral and granular processing of sound grains and audio signals. This choice was made with the intention of attaining data-driven **gestural** control over the produced sonorities (i.e. simply playing the instrument), ultimately striving for balance between real-time data-driven and composer-driven control. Nevertheless, despite being primarily designed for live performances, the output of this modified synthesizer can and has been used as raw material in many of the fixed compositions in this portfolio.

The modifications on cataRT are implemented within the *Catart.lcdm corpus* sub-patch. These were updated on two further occasions with the intention of fostering handshaking with two other patches, The *Data-driven Animation Patch* for the work *Malignant Angiogenesis* and the *Data-driven Ambisonic Spatializer and Make noise Modular Synth Modulator*, which are described further below.

**Figure 5. 4** demonstrates the modified *Catart.lcdm corpus* sub-patch. As it can be seen, the parameters under data-driven and/or manual (user) control are highlighted using red and blue markers respectively. However it should be pointed out that the balance demonstrated here between data and user control is specific to one instance of this patch which runs together with the *Data-driven Ambisonic Spatializer and Make noise Modular Synth Modulator* patch, and was achieved through trial and error. Other balance layouts can be easily achieved with minor modification.

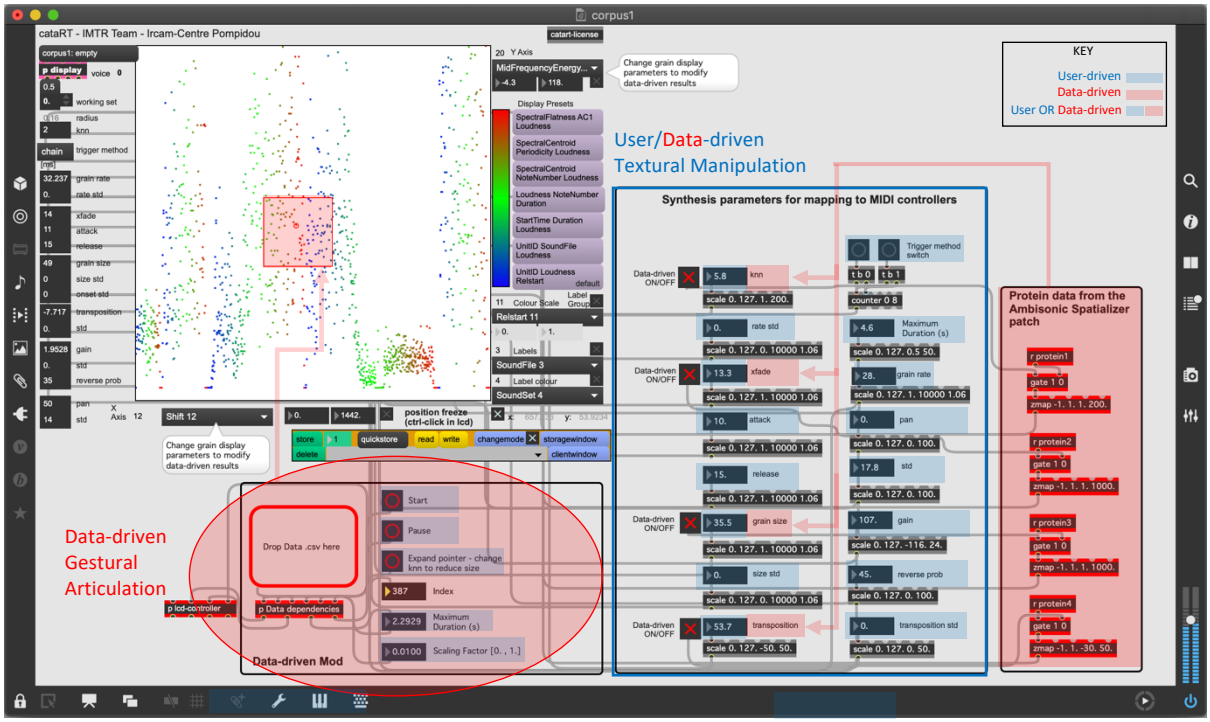



Figure 5. 4 – Modified cataRT.lcdm corpus

As pointed out above, the main aim of the modification made to cataRT was to achieve data-driven gestural articulation. Nevertheless, some minor user control is also provided for the latter, i.e. *Scaling Factor*, *Maximum Duration* (speed of cursor trajectories), *Starting/Pausing* (the data driven movement of the cursor) and the *Trigger* button (increases the size of the cursor).

Textural manipulation control is left to the user for the most part. However, as demonstrated in **Figure 5. 4**, some of the synthesis parameters in this area can be assigned data-driven control using toggle switches. These are highlighted by two-fold red and blue markers. Further details regarding the implementation and programming of this modification can be found in the appendix.

### 5.3.1 Augmented gestural input via external MIDI controllers

As a performance interface, the modified cataRT works best with MIDI controllers for quick and easy control over user-driven parameters. In the multiple instances of its use in improvised performances, I used an ICON Platform-M Midi controller (iCON Pro Audio, n.d.) with pads, faders and knobs which depending on the piece, could be mapped to any preferred arrangement of the user-driven parameters.

Even though the user-driven parameters primarily affect the textural characteristics of the synthesis output, the tactile and immediate nature of using physical controllers provides the opportunity for human gestures to also take shape and emerge, augmenting the data-driven gestures produced during performance. This further emphasizes the primary aim of this modification, and effectively creates a dialogue between the performer and the data. The use of linear trajectories results in the data-driven gestures sounding more systematic and automated, which creates an interesting contrast when juxtaposed with the performer's gestural input. Nevertheless, if necessary in the future, with little modification the latter trajectories could also be produced using exponential curves as well.

The following chapters feature commentary on the fixed compositions which were realized, primarily using sonified material generated by the three patches outlined above. Please note that an updated version of the *Modified Data-driven cataRT* was used extensively for live improvised works whose commentaries can be found in Chapters 13-15.

# Chapter 6:

# HOURS OF ONCOGENE – MVTS. I, II & III

## 6.1 Introduction

This work was my first ever attempt at composing fixed pieces using sonified material. Admittedly, as inexperienced and fresh as I was to data sonification, I believed then that the value of works utilizing data sonification, rested entirely in the fact that there was simply a dataset responsible for the produced sonic material. In other words, "the data is everything and all that really matters". Of course, over the next few years of working on this project, I discovered that is certainly not the case.

Stemming from the above mentality, I set out to utilize the outputs of the *Data Handler* and *AddSynth* Max patches which were described earlier, and compose a piece, which ended up as a three-movement composition. The most fundamental distinction between this work and most of the other pieces in my portfolio is the approach towards the use of data sonification, and subsequently the produced material in the composition. With *Hours of Oncogene*, the use of the sonified material is primarily *generative*, except for the broader conceptual background of the work (described further below), and as outlined earlier, the design of *Data Handler* and *AddSynth* patches, which can be considered to encompass both *allusive* and *curatorial* elements. Instead of focusing on conveying any specific concept or information regarding the data through the music to the listener, my aim was solely to explore the inherent sonic and musical potential of the produced sonifications.

## 6.2 Commentary

This aim and the composition of this piece together served as a very important experiment for myself, as up to that point, I had very little experience working with material that was from my perspective "indeterminate". Therefore, writing *Hours of Oncogene* was a fruitful and productive exercise in exploring the extent of my control as the composer while working with the novel sounds and patterns discovered through the sonifications of data.

One notable importance of this piece which I find now, looking back at it, is that it set a precedent for my broad, musical aesthetics and composition language, which also brought with it an open-minded and accepting attitude towards the use of the sonified material. In addition, this attitude also has roots in my standpoint on data sonification and how it can be an embodiment for the 'intangible', creating as a result a genuine fascination and receptivity towards 'the sounds of protein fluctuations', or more artistically reduced in the mind, as 'the sounds of proteins'.

With the latter concept, the sonified synthesized tones, and the recurring theme of programmatic, systematic and machine-like characteristics attributed to proteins and how they interact within the cell with regard to each Hallmark of Cancer, I imagined the inner sound-world of a cell becoming cancerous as weird, chaotic, mysterious and dark, and even digitalized (bearing a link to computational biology and the data-type), with the occasional implication of harmony through the use of overlayed indefinitely and ambiguously pitched material--harmony which is disrupted and derailed during this transformation to a malignant state.

All three movements of *Hours of Oncogene* have a rounded form, ending with an echo of their opening sections. This return also emphasizes the repetitive and process-like mechanisms of proteins. Another notable aspect of the composition of these movements is the design of the *Data Handler*, and its operation. Specifically, how significant proteins are looked up in the systems-level dataset in a time-based manner, i.e. the timed process of bringing out the signal from the noise. The resulting sound-world from this process is one that is predominantly arbitrary, or as I came to call it, *the random void*, with the occasional emergence of the sonification of a significant protein. This process is also an analogy to how the resulting datasets from such experiments are explored and cross-referenced. The latter sonifications are preserved in their entirety, and raw state, in the composition process and are not manipulated or processed much further.

### 6.2.1 Mvt. I

This movement has a particular focus on the exploration of pitch-based, pseudo-melodic and rhythmic motifs, superimposed over textural material. The overall harmonic language remains ambiguous and indefinite. There is no strong and clear sense of a tonal center, however specific motifs do occasionally give a transient impression of this. For instance, the whistling tones at [0:35]; or the harsh and scratchy sawtooth motif at [0:45-0:50], roughly hitting a perfect $5^{th}$ descent (approx. G → C), followed by a minor $3^{rd}$ rise (C→ $E_{\flat}$) (simple C minor triad); or the triple-time motif fading in at [1:23] which implies a

grounding in ($G_{\sharp}$), are examples of the latter.

These motifs are the sonifications of significant proteins which are looked up in the source dataset by the *Data Handler*'s *Category Matching*. Therefore, they have been preserved in their most raw and unprocessed form, and iterated repeatedly to highlight their importance. The more textural sound-objects used in conjunction with these motifs are the results of the arbitrary operation of *The Data Handler*, or *the Random Void.*

The overall structure of Mvt. I can be broken down to an **A** → **B** → **B**$^{*}$ → **C** → **A**$^{*}$ form, where **A** and **A**$^{*}$ serve as introduction and ending echo respectively. **B** and **B**$^{*}$ are the sections where the motifs outlined above are introduced and developed further. Leading then into **C** [1:59], which serves as a separate, break section, featuring an elongated crescendo of a sonic compound of several layers of pure tones and modulated noise. **Figure 6. 1** below provides an overall view of this movement's structure.

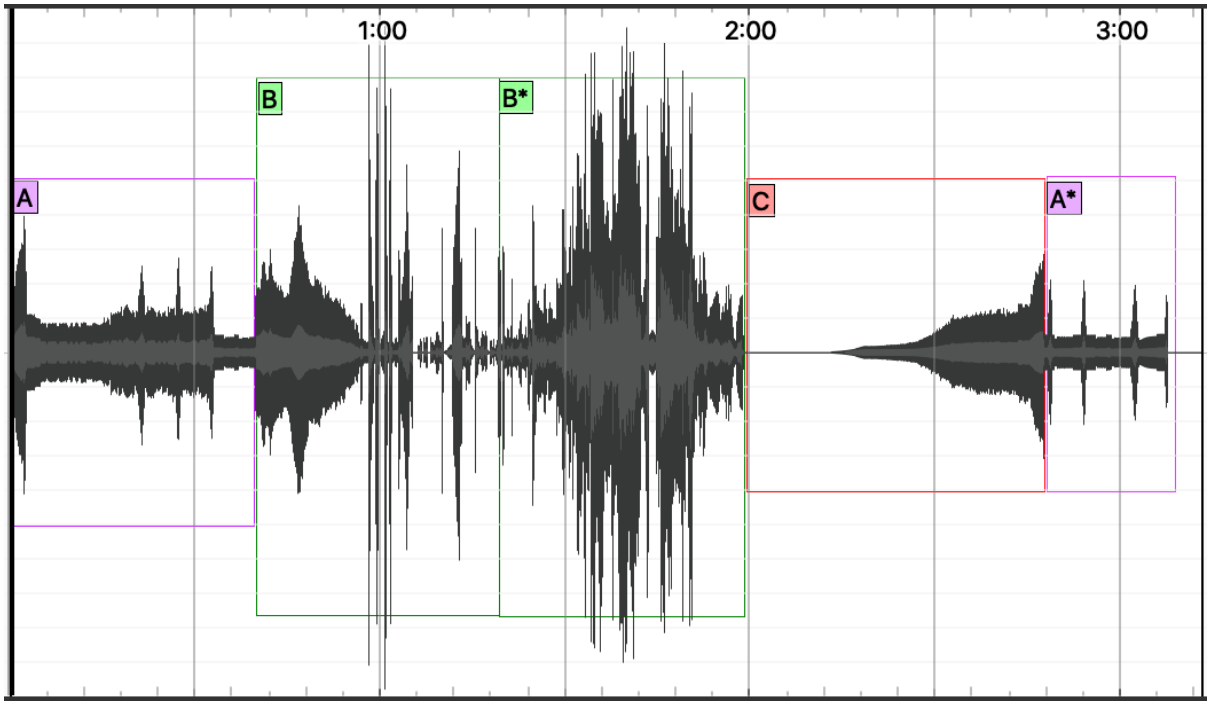



Figure 6. 1 – Hours of Oncogene Mvt. I Sections

### 6.2.2 Mvt. II

Movement two, is similar to the first in its primary compositional focus, which is to explore the interaction of textural material with gestural motifs. However, the main difference here is having less of a focus on pitch-based, melodic material. For example, the only pitch-based motif used here is at [0:59-1:10], where its subsequent pitches can be approximately identified as (C → C♯ → C → F). The rest of the motifs in this movement are gestural and not pitch-based, e.g. the high-frequency, chirp-like sound at [2:18].

Another notable composition strategy in this movement is the exploration of space in the sound-world using reverb [most notably at 1:09, 1:42 and 3:18]. In these points, through the sudden emergence of reverb, we are confronted with a sense of space on a much vaster scale, compared to the rest of this movement, and also the previous one. In addition to the reverb, the inclusion of ominous-sounding, single-voice and multilayered drones [e.g. 0:00-0:50, 2:20-2:50], and the use of the dramatic, accented

bass hits [1:10, 2:40-2:50 and 3:33] are specific elements which became integral parts of my composition language in this portfolio, and are therefore recurringly used in other compositions.

The overall form of Mvt. II is very similar to Mvt. I. It is a rounded **A** → **B** → **A**$^{*}$, with the **A** and **A**$^{*}$ sections as the introduction and ending echo. The **B** section is where various motifs are introduced and developed. This section consists of the juxtaposition of the pitch-based and other gestural and rhythmic motifs. Similar to Mvt. I, **B** also encompasses a break, with a gradual crescendo of a multilayered drone, over which, other gestural motifs (incl. the high-frequency, chirp-like motif) are introduced and developed. **Figure 6. 2** below shows the overall structure of this movement.

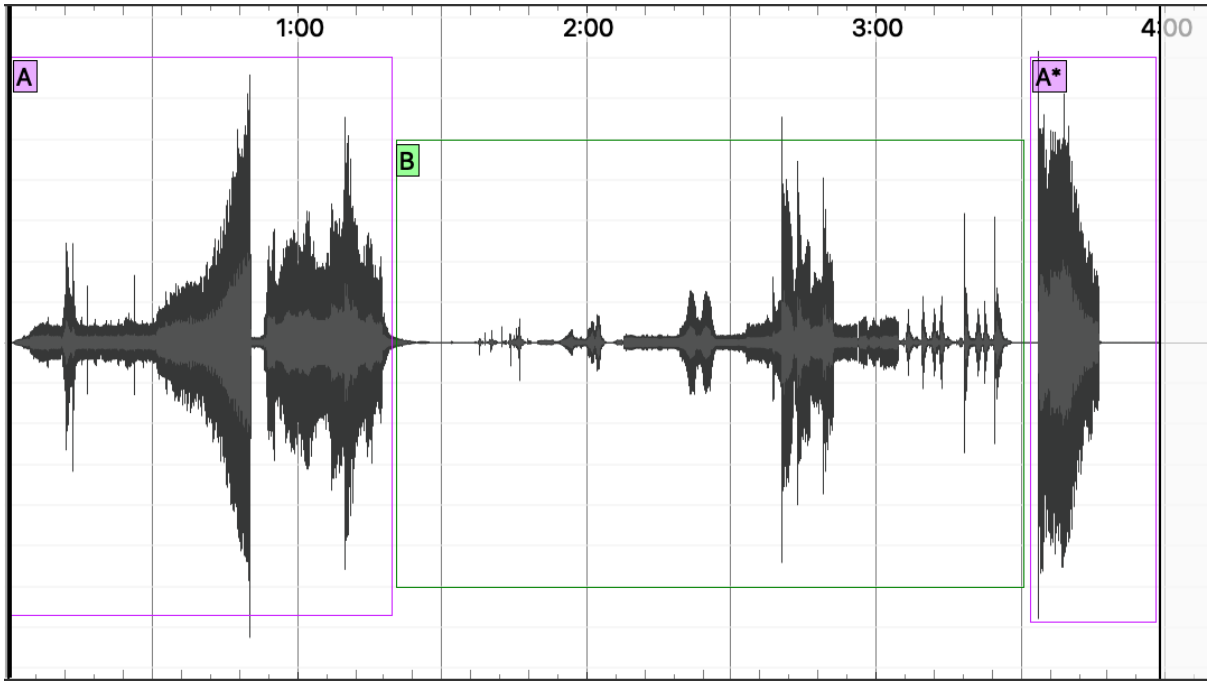



Figure 6. 2 – Hours of Oncogene Mvt. II Sections

### 6.2.3 Mvt. III

This movement takes an even more harmonic and rhythmic focus compared to the previous two. While the sound world bears certain obvious similarities in the primary use of synthesized pure tones as raw material, the main adopted technique here (and which sets it apart from the previous two movements) is data-driven concatenative synthesis (*Modified cataRT*). This resulted in the grainy, and coarse texture of the main pitch-based drones in the opening, and also of later ones throughout the piece.

Concatenative/granular synthesis subsequently became an integral part of my composition practice in this portfolio.

The raw sound material used for the process of concatenation was in fact the same source material generated by *Data Handler, FM synthesis, and AddSynth* used in the previous movements. This resulted in the emergence of more definitely pitched elements intrinsic to the raw material, which also gave this movement a more direct focus on harmonic progression and development. The opening drone is rather firmly rooted in (F-Lydian). Although there is a rich polyphony of both definitely and indefinitely pitched tones that make up this drone, the more audibly identifiable ones are approx. (B) and (C), with an (F) in the bass, which are laid out as a chord with intermittent alternations between the (B) and (C).

Same as the other two movements, the overall form is rounded, and can be broken down as **A → B → C → A***, with **A** and **A*** being the introduction and echo. **B** features rhythmic material, which can be primarily identified as being in approx. 4/4, with the occasional augmentation to 6/4 and 7/4. This section is relatively sparse in contrast to the busy and drone-based others. The repetitive rhythmic gestures at [1:15], are made up of data-driven pops and clicks, combined with a pair of resonant band-pass filters set at 65Hz (approx. C2) and 95Hz (approx. G2). Due to the approximate nature of these pitches, which is the result of the technique of acquiring them, a range of harmonic and inharmonic frequencies bleed through as well--rendering this perfect $5^{th}$ interval a rather ambiguous and masked chord, which serves as a continuous backdrop, onto which non-pitched, textural and gestural interactions are explored.

Section **C** sees a return to the coarse drone narrative of the introduction, which is explored further harmonically, before arriving back at the (F-Lydian) chord in the echo (**A***). This exploration initially takes our drone narrative to the minor $3^{rd}$ interval between the pair of (D) and (F), followed by the $5^{th}$ interval between ($E_\flat$) and ($B_\flat$), and finally to ($D_\flat$- Lydian: $D_\flat$ + F + G), which sets the scene for the return to the introduction's (F-Lydian), in the echo (**A***). **Figure 6. 3** below depicts the overall form of this movement.

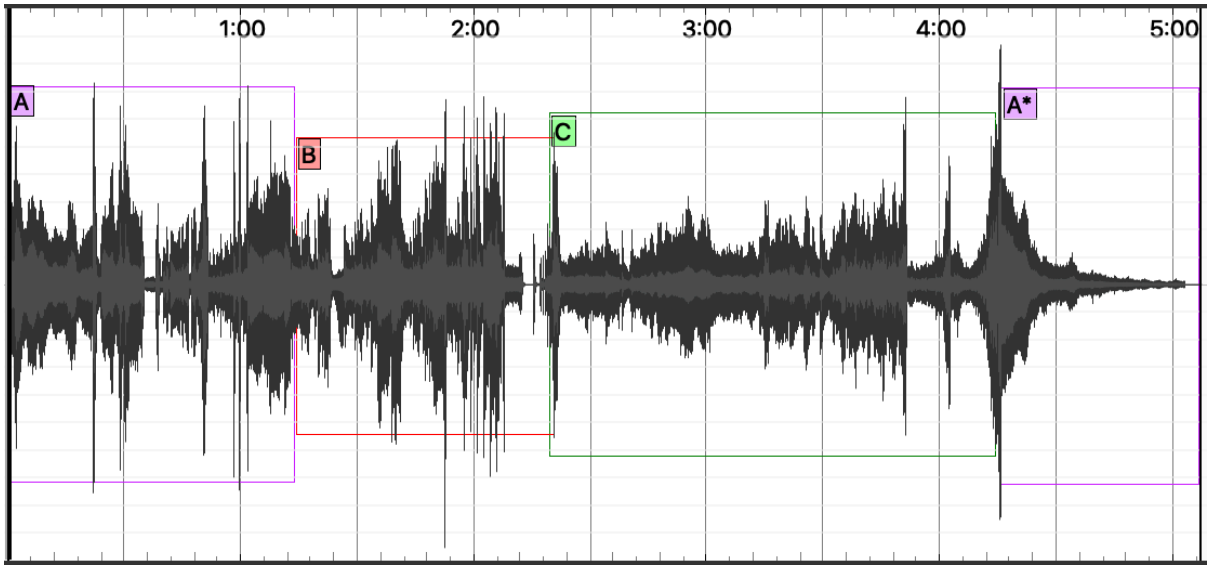



Figure 6. 3 – Hours of Oncogene Mvt. III Sections

# Chapter 7:

# THREE HALLMARK ETUDES

## 7.1 Introduction

These short etudes include my earliest attempts at sonically conceptualizing the narrative of three of the hallmarks of cancer, while working solely with the synthesized sonified material, generated by the combined operation of the *Data Handler* and *AddSynth* patches. These etudes primarily stand as proofs of concept for the future work I undertook regarding the composition of fixed pieces, representing the narrative of each hallmark of cancer musically and in an allusive manner.

## 7.2 Commentary

The main area of compositional focus in each etude is the use of sonic metaphors, primarily informing overall form and progression, as well as gestural articulation, to achieve a conceptual sonic model. These metaphors are drawn from abstracted versions of the descriptions of each explored hallmark whose detailed versions can be found in the *Hallmarks of Cancer* article (Hanahan and Weinberg, 2011). These are outlined in **Table 7. 1** below.

| Hallmark Etude | Hallmark Description | Conceptual Sonic Model |
|---|---|---|
| **1- Sustaining Proliferative Signaling** | The most fundamental trait of cancer cells involving the ability to sustain chronic proliferation.<br><br>**Intracellular tyrosine kinase domains** release signals within the cells that regulate progression through the cell-growth-and-division cycle. These signals are thought to be transmitted in a temporally and spatially regulated fashion from one cell to its neighbors. | Multiplication and proliferation of assigned sonic events to normal cells (The 'Random Void' sound-world) is demonstrated. These maintain a steady pace in occurrence, followed by a rapid increase towards the end of the etude.<br><br>A distinct sonic event is assigned to **Intracellular tyrosine kinase domains**--connecting different sections within the piece, and representing the temporal and spatial manner of cell-growth signaling. |
| **2- Evading Growth Suppressors** | Cancer cells circumvent powerful programs that suppress cell proliferation via **tumor suppressor genes.**<br><br>The two prototypical tumor suppressors encode the **RB** (retinoblastoma-associated) and **TP53** proteins--they operate within cellular regulatory circuits which decide whether cells are to proliferate, or go into senescence and cell-death programs.<br><br>**RB** act as critical gatekeepers which transduce cell-growth inhibitory signals from outside of the cell. **TP53** receives inputs from stress and abnormality sensors within the cell. | Distinct sonic events are assigned to **RB** and **TP53**.<br><br>Similar or identical sonic events (quotations) from previous hallmark etude (**Sustaining proliferative signaling**) are included.<br><br>**RB** and **TP53** sonic events reduce or cut off the sustaining-proliferative-signaling quotations (normal cells). **RB** interacts with external sonic events, while **TP53** interacts with internal sonic events (relative to the sound-world).<br><br>**RB** and **TP53** sonic events fail to reduce or cut off the sustaining proliferative signaling quotations (cancer cells). |

| Hallmark Etude | Hallmark Description | Conceptual Sonic Model |
|---|---|---|
| **3- Resisting Cell Death** | Programmed cell-death by apoptosis acts a natural barrier to tumorigenesis, which is initiated in response to various physiological stresses during tumorigenesis.<br><br>The trigger to apoptosis is controlled by counterbalancing pro- and anti-apoptotic members of the **Bcl-2** family of regulatory proteins.<br><br>*T*wo pro-apoptotic proteins **Bax** and **Bak**. Disrupt the integrity of the cell's outer membrane and cause the release of **cytochrome c,** and other pro-apoptotic signaling proteins, leading to the programmed death of the cell.<br><br>A DNA-damage sensor, functioning via the **TP53** tumor suppressor, can increase the expression of pro-apoptotic proteins in response to substantial levels of DNA breaks and other chromosomal abnormalities.<br><br>Tumor cells can evade apoptosis by inducing the loss of **TP53** tumor suppression functionality (switching off the DNA-damage sensor); or by increasing the expression of anti-apoptotic regulators **Bcl-2/Bcl-$X_L$**; or by downgrading pro-apoptotic factors (**Bax/Bak**). | A distinct sonic event is assigned to **cytochrome c** and introduced gradually into the sound-world.<br><br>The Random Void sound-world undergoes multiple gestural alterations with the introduction of **cytochrome c**. A repeated fade-in gesture and consecutive reduction of the 'Random void' sonic parts represent the disintegration of the cell (Apoptosis).<br><br>Distinct sonic events are assigned to both, pro- and anti-apoptotic regulators, i.e. **Bax/Bak** and **Bcl-2/Bcl-$X_L$** respectively.<br><br>The **TP53** sonic event is quoted from the **Evading Growth Suppressors** hallmark, coupled with its effect in increasing the presence of pro-apoptotic regulators' events (**Bax/Bak**)<br><br>The loss of **TP53** functionality is demonstrated. This leads to a rise in the presence of anti-apoptotic (**Bcl-2/Bcl-X**) events, while simultaneously decreasing the presence of pro-apoptotic (**Bax/Bak**) events. |

Table 7. 1 – Three Hallmark Etudes Conceptual Sonic Models

## 7.3 Retrospective

While these short etudes served as very important exercises in working with the sonified material in conjunction with the narratives of the hallmarks of cancer, the reality of writing long, fixed pieces was indeed utterly different. Hence, the resulting works are also entirely different from these three etudes. The most striking difference was in the extent of my own freedom in the composition process, to deviate in some parts from the story I was trying to tell, in the favor of maintaining musical intrigue. In other words, I ended up exercising a far greater degree of control in the longer composition, compared to these etudes. This was also as a result of realising that the contextual information regarding the biomolecular processes that I was trying to convey through the music were in most cases too specific and complex to be interpreted by the listener, and therefore required a greater level of abstraction. This also resulted in my metaphorical links becoming contextually wider and deeper in terms of how I developed various compositional elements (e.g. overall form). To put it in simple terms, for the short duration of the etudes, remaining absolutely true to the overall narrative (and the listener – with the aid of programme notes – being able to also follow this) seemed more plausible, compared to the longer compositions. Therefore, in the rest of the works in this portfolio, I have taken a less puristic stance towards the data and its context, and instead allowed my artistic and compositional voice to take more control, ultimately striving for an effective balance between the two through allusion to the scientific context.

# Chapter 8:

# SUSTAINING (AN ECOLOGICAL NEOPLASM)

## 8.1 Introduction

Sustaining was the first, long conceptual piece in this portfolio. At the time of its conception, given the fact that I was at the very beginning stages of my research, the possibilities seemed endless. Referencing the same compositional outlook mentioned earlier--the search for the shock factor--I decided to adopt an experimental compositional approach in writing this piece, which in hindsight, might have made the listening experience too complex and obscure.

The foundation of this approach is rooted in superimposing two distinct and divorced levels of conceptual narratives on top of one another: Anthropogenic Climate Change Denial, and Cancer. At an immediate glance, this superimposition suggests "*Climate Change = Cancer of the Planet"*, and as simplistic and preliminary it might seem, this description is not entirely far off from the core message of this piece.

Despite the increasing consensus over the sobering reality and significance of anthropogenic climate change in today's world, the malignant spread of discord and denial over the subject still remains an inimical issue in the face of impending, irreversible consequences. While politicians and world leaders fail to implement effective and sufficient policies to battle this plague of the planet, proponents of its denial continue to sow doubt into the minds of the public by ignoring the scientific evidence and referencing the political agenda of science or questioning the premise of the argument and the validity of the data. They hold talk talks, interviews and attend debates where they spread out this rhetoric, which then continues to circle on public media platforms. Out of frustration for this spread of misinformation, I started imagining anthropogenic climate change as a neoplasm whose growth was, among other causes, *sustained* by this discord, and the denial rhetoric which 'signaled' and fueled it.

## 8.2 Commentary

Seeing climate change as cancerous growth, my aim was to draw a metaphorical link in the mind of the listener between the rhetoric of climate change denial and the constant cellular growth and proliferation signaling in cancer cells. To quote Hanahan and Weinberg:

> Cancer cells become masters of their own destinies by deregulating the otherwise carefully controlled production and release of growth-promoting signals that instruct entry and progression through the cell-growth-and-division cycle.

To achieve this task, I decided to use raw sonic material whose sources are in stark contrast with one another: organic, fragmented human speech, gathered from recordings of debates, interviews and lectures featuring climate change deniers making their arguments; and synthesized, granular, data-driven sounds--generated using a variety of approaches, including Parameter-mapping, FM synthesis sonification, and data-driven concatenative synthesis, using the *Modified Data-driven cataRT*. It is noteworthy that in my mind, the juxtaposition of these two sound-worlds creates a tension which references an unfamiliar and abstract duality. One that stems from the idea of cancer as an unnatural element, distorting, disrupting and consuming the natural order of the cell which can ultimately lead to it becoming a malignant tumor.

As far as my intention goes with adopting the latter approach, I wanted to create a two-fold conceptual structure, consisting of the far more abstract and unfamiliar concept of *Sustaining Proliferative Signaling* in cancer cells, and the more concrete and tangible one of climate change denial--keeping the latter on the foreground, represented as a gradually amassing excess of speech sounds and their interactions and development; and the former, dictating the more primary and structural elements of form, progression and overall gestural qualities, in the background.

This is primarily reflected in how the speech element is used in the composition of this piece, which is significant. As pointed out, speech fragments are gradually processed into a surfeit over the course of the work, reaching a climax of maximum presence and density at the very end of the piece [8’11”].

Meanwhile, a selection of words and sentences related to the arguments and strategies used by climate change deniers (outlined earlier), are iterated in such a way that while they remain intelligible to the listener, they are also obscured by the overlapping of different speech fragments, as well as the enormity and density of the entire plethora of sound-objects. This is intended to prevent the spoken word content from drawing too much focus from the listener, and instead, draw their attention to the more holistic and spectral transformations occurring between the all present sound-objects. In a way, encouraging the listener to regard the speech the same as all the other sound-objects and not as the main narrative device, whilst still maintaining the purpose of conveying its content.

The mass of almost-unintelligible speech sounds was inspired by the 2001 work '*Babe*l' by the artist *Cildo Meireles*, which is displayed at the Tate Modern Museum in London (Meireles, 2001). There, the artist has constructed a physical and sonic sculpture made out of an abundance of radios of various models, sizes and shapes, which are piled onto one another in order to create a 3-meter high, cylindrical tower. Moreover, each radio is tuned to a specific network around the globe and the result, referencing the biblical story from the book of Genesis, can perhaps be most concisely described as *The Tower of Incomprehension* (Barson, 2011). While Meireles's original work has its own conceptual origins which are beyond the scope of this commentary, in this piece, the build-up to the incomprehension, nonsense, or fake-news references the absurd nature of climate change denial rhetoric in a derogatory and ironic way. More specifically, this absurdity is reflected in how the proponents of climate change denial use the dialectic and scientific method – in a biased way of course – to prove their misguided arguments. At a deeper conceptual level, the latter bears yet another metaphorical link to the nature of cancer, and that is the misuse of logic and reason for cementing harmful arguments against climate change. Analogously, one can also regard cancer as taking advantage of the existing biochemical mechanisms and systems on the cellular level, for its own malicious growth and progress.

Moving away from the concepts and towards the actual composition, the overall structure of *Sustaining* can be best described as an *A-B-C-A* form--with each section exploring the interactions of speech fragments, over a variety of data-driven sonorities and textures, as well as gestures, according to the

narrative of this particular hallmark of cancer. The opening's relentless, ominous, and abrasive drones, with the layered whirling gesture on top [0'00" – 3'17"], are intended to invoke a sense of unease and tension. This is emphasized even more through the use of subtle pulse-like modulations within the drones themselves in order to permeate a sense of progression and movement. Meanwhile, there are FM-synthesized, cell-phone-like beeping sounds, which signify, almost in a literal way, the 'Signaling' that is of cell growth and division. These are also heard repeatedly in multiple parts of the piece [1'45",5'29", 8'13", etc.] and at times morph into and manifest as ambiguous melodic motifs [2'03", 2'44", 3'05", 4'56", 5'54", etc.]. It must also be pointed out that the comparison between the behavior of normal and cancerous cells in terms of regulating cell growth signals, provides a directive for the way this piece progresses through each of its sections, which is an elongated *crescendo*, arching over not only the dynamic intensity but also the gestural presence and development of the underlying sound-objects. This *crescendo* (growth) is seemingly contained and dampened multiple times [3'17",4'30", 6'04", 7'55"], only to lead towards an ultimate surrender at the climactic end of the recapitulated final section.

One important section of this piece is '*C*' [6'04"- 8'10"], which lands on an entirely data-driven, harmonic chord progression, consisting of sawtooth drones, spread over ambiguous and detuned intervals. With very little processing except for pitch-preserved, time-stretching, this contrasting harmonic landscape serves as a 'break' in the sound-world of the piece up to that point. In addition, it lays the basis for the build-up to the climax of the piece.

Just prior to the latter climax, the speech fragments sporadically converge onto a single word, "*Totalitarian*" [8'05"]. This is the closest proximity of the two, separate, underlying concepts of this piece. The metaphor, albeit understandably obscure and ironic, is one that paints a fantastical image of cancer as an autonomous and autocratic cellular ruler of the cell's biochemical subjects (i.e. Proteins and RNAs). The irony here also points back to the spoken rhetoric, which was extracted from a speech by a climate change denier, describing environmentalism as a totalitarian effort—a preposterous claim given that it is authoritarian politicians who are most guilty of propagating climate change skepticism.

One important developmental strategy throughout the work is the spectral changes and evolution of both the speech element and the underlying drones. For the latter, the heavy use of continuous drones allows this evolution to be observed by the listener, as we naturally tend to focus more on the spectral qualities of continuous and repetitive sound-objects (i.e. drones), due to the minimal nature of their gestural information.

From a broad gestural perspective, *Sustaining* is a predominantly drone-filled piece, and in addition to the more technical and practical reason for this choice outlined above, the conceptual reason behind it stems from my intention to convey a sense of relentless continuity derived from the concept of cancerous growth signaling--an unending and malignant unfolding of events that signifies the incessant proliferation of climate change denial rhetoric, and the *sustaining of an ecological neoplasm*.

## 8.3 Retrospective

Initially, along with writing this work also came the idea to explore the relationship between other dangerous ideologies and cancer, e.g. neocolonialism, neofascism, xenophobia, racism, religious extremism, etc. However, at the time I was not entirely sure whether this was the direction I wanted to take in this portfolio instead of focusing on the science behind cancer. With the advice of my supervisors, I decided to go ahead with composing this piece as an experiment, which allowed me to realize that I wanted to focus solely on the latter, i.e. the science of cancer research.

As pointed out earlier, judging from the mixed feedback I acquired on this piece from listeners of various levels of experience with EA music, I retrospectively came to the conclusion that *Sustaining* does not entirely manage to hit its target in terms of conveying the intended conceptual depth and intricacies to the listener successfully. This is perhaps mainly due to the overly-complex and contrasting concepts under exploration, as well as the abstract and obscure nature of the sonic metaphors, which was likely to also occur with exploring any other complex socioeconomic or sociopolitical issue. Coupled with the diversity and business of the entire sound-world, the piece can perhaps leave the more unequipped listener confused and at times wondering: “What on earth is going on here?”. Nevertheless, considering

the presentation format of this work, i.e. Electroacoustic concert music to be diffused, the accompanying medium of the concert programme note can be a useful contrivance for providing some much-needed context for the listener. And at the very least, it can show them the path towards understanding *Sustaining*'s rather abstruse symbolism, as well as--to reference Meireles's work once more-- its 'incomprehensible' message.

# Chapter 9:

# (RESISTING) CELL DEATH BY APOPTOSIS

"*Programmed cell death by apoptosis serves as a natural barrier to cancer development.*"

*" Tumor cells evolve a variety of strategies to limit or circumvent apoptosis. Most common is the loss of TP53 tumor suppressor function, which eliminates this critical damage sensor from the apoptosis-inducing circuitry."*

*" Tumors may also evade apoptosis by increasing expression of anti-apoptotic regulators, or of survival signals, by down-regulating pro-apoptotic factors (Bax, Bim, Puma), or by short-circuiting the death pathway intercepting stress signals from outside of the cell."*

(Hanahan and Weinberg, 2011)

## 9.1 Introduction

Personally, I would consider this piece an important part of this compositional portfolio, in the sense that it tells not only the story behind the interactions of proteins within the cell through the scope of this specific hallmark of cancer (allusively), but also in a way a personal story of my own, which inspired the initial idea for this work. From a technical perspective, this piece utilizes an array of sounds featuring sonified material generated through granular and concatenative synthesis, and recorded sounds from the environment at the laboratories of Barts Cancer Institute, pieced together in REAPER.

What sets *Cell Death by Apoptosis* apart from the other pieces I had written up to that point, is the inclusion of harmony created by the layering of pitch-based, data-driven drones. This harmonic landscape perhaps owes its emergence to a deeply emotional and personal encounter with cancer over the course of my research, which fueled its significance in this piece as the fundamental idea from which the rest of the work grew into existence.

## 9.2 Commentary

During the summer of 2019, around 6 months before the first seed of this piece was conceived, I was unexpectedly confronted with the news of my father having been diagnosed with cancer and awaiting a very tough operation, to be followed by extensive rounds of chemotherapy. I had to set aside all of my work and travel back to Iran to support him and the rest of my family through this ordeal. What I did not anticipate at that point was how this experience would almost naturally and on a sub-conscious level bleed into my music. Witnessing first-hand how this vicious disease, whose biochemical culprits I had been - with almost a child-like sense of fascination - studying, sonifying and making music about, tormented and had brought to heel my father who had always been a symbol of strength and sheer will power to me, left a deeply emotional mark on me and planted the seed of a simple image in my mind. One that might perhaps hit close to home for anyone, given the year 2020 and the raging covid-19 pandemic: the image of an epic hero, regardless of all their hard-fought and won battles, unjustly brought down to their knees by an invisible source. Much like the fall and death of *Enkidu* to the curse-ridden disease, in the *Epic of Gilgamesh* (Foster, 2018).

Putting the philosophical and psychological implications of such a brush with reality aside, out of this fantastical image came the sense of an event (a sonic event) that evokes a sense of great power and will but also melancholy and tragedy--the tragic succumbing of a hero to disease. This emotionally-charged concept perhaps sits at the root of the harmonic climax of *Cell Death by Apoptosis* and serves as a backdrop to the more immediate, textural events and interactions in the foreground, which are referencing the biochemical interactions in the cell, tied to this specific hallmark of cancer. The grainy and distorted but energetic texture of the drones and their dismal harmony of compound minor $6^{th}$ and minor $9^{th}$ intervals, following a crescendo and pitch slide up, are intended to convey this combination of strength and sorrow.

Moving up a level in terms of the narrative depth of this work, the majority of the piece's form and direction is structured around the narrative of *Resisting of Cell Death* by cancer cells and its comparison with the behavior of normal cells. As pointed out earlier, Apoptosis is described as one of the most

fundamental and natural barriers against cancer development. Every normal and healthy cell in our body will naturally go into a dormant but metabolically-active phase known as *Senescence,* in which the cell loses its power to grow and multiply but remains functional. This is followed by the programmed disintegration (death) of the cell, which is referred to as *Apoptosis.* Hanahan and Weinberg describe Apoptosis as a piece of machinery, a systematic process. Tumor cells develop multiple strategies that allow them to interrupt or circumvent this program (Hanahan and Weinberg, 2011).

Stemming from this contrasting behavior of normal and tumor cells when it comes to cell death, the form and narrative of this piece can perhaps be divided into two main sections--an A-B form (wrapped between a prelude and an epilogue), whose two parts are conceptually and sonically intertwined and connected by the concept of cell death. The A section represents the normal (natural) death of cells, featuring the introductory exposition of the harmonic material and textural interactions which bear abstract metaphoric links to the programmatic quality of apoptosis and the normal functions and interactions of the involved proteins and genes, namely *TP53, Bax, Bim and Puma.* This exposition leads into the climax of the piece which boldly (and also perhaps musically) represents the full functionality of the machinery that is normal cell death. The climactic section is thus imbued with sonic symbolism to the idea of machinery through the primary use of rhythmic, metallic, hammer-like hits, which are layered onto bass-drum-like hits, and which (in a step-like and mechanical way) drive this section forward in a slow decrescendo towards the next.

The second half of the piece, features a brief bridge section that introduces new sound-objects and interactions which to my mind represent something alien and unheard of up to that point in the piece: a reference to the altered functionality of the mentioned proteins and genes that would normally cause the cell to go into apoptosis. However, this bridge section also features the similar but altered hammer-like hit, only this time they are introduced in a more rhythmically temperamental and irregular fashion, contrasting their previously mechanical and symmetrical characteristic, and bearing reference to the machine being broken or malfunctioning.

What follows next is the same harmonic drones from the previous section, this time transposed down by a major 6th interval. The result is a darker and more insidious harmonic landscape, which lacks the mentioned mechanical sound-objects, as well as the textural interactions layered on top. Instead, it emerges together with an ambiguous, siren-like gesture, and progresses in a slow crescendo to materialize into the main subject of the piece. This repetitive siren-like sound, which was also foreshadowed briefly earlier, is a metaphorical sign of the cell having become cancerous. In addition, this is reinforced by a simple quarter tone ($B_{\flat}$) which, much like a complimentary bittersweet signal, is heard only intermittently.

It is also worth mentioning that one important gesture which is repeated throughout the piece is a sudden cut in the transitions between sub-sections following their gradual build-ups. This sharp cut symbolizes a drastic and almost cinematic change in the perspective of the listener. Also, it more broadly bears reference to the suddenness and finitude of the concept of death. This gesture is implemented in various parts of the piece where the narrative of the hallmark of resisting cell death becomes disjointed – much like a sudden flash-back or flash-forward in a film. Examples of this include the cut in the foreshadowing of the siren-like sound, or in the epilogue where the listener is suddenly and metaphorically dragged out of the sound-world of the inside of a cancer cell resisting death, and thrown into the outer physical world: the soundscape of the laboratories at Barts Cancer institute. The latter short epilogue features processed sounds recorded directly from a Mass-Spectrometer: a device responsible for measuring and generating the protein fold-change data, utilized in the sonification process in this PhD project.

# Chapter 10:

# EVADING (GROWTH SUPPRESSORS) – PATCH & COMPOSITION

## 10.1 Introduction

This chapter features a brief technical overview of the *Data-driven, MIDI VST Synth* Max patch, followed by commentary on the fixed composition titled *Evading (Growth Suppressors)*, which was realized using raw sonic material generated solely by the operation of the latter patch.

## 10.2 Data-driven, MIDI VST Synth

This system was designed with the goal of creating a data-driven ensemble of instruments plus electronics, bringing the synthesized sonifications of *AddSynth* together with data-driven instrumental parts. This mixed-media ensemble functions as an interface used for composition or possibly live performance.

The instrumental parts are produced by the data-driven scrambling, or 'shredding' of the events of raw input MIDI data. This input data can be a pre-recorded MIDI file, or recorded live using any instrument or pad capable of transmitting MIDI events on any MIDI port. Moreover, the use of MIDI was adopted with the intention of yielding notated parts using MaxScore (MaxScore 2, n.d.) for live instrumental performance. However for the time being, the latter remains a future development goal for this interface. For the purposes of demonstration and generating raw material for composition, these instrumental parts are played using VSTs. The patch can accommodate up to 6 instruments. In case of live performance, each of these will need to be closely captured using directional microphones, and the signal sent back to the patch for further processing and amplification.

### 10.2.1 GUI & Design Overview

**Figure 10. 1** below provides a glimpse of the GUI of this instrument, while **Figure 10. 2** demonstrates its overall design. The various key modules in this design are elaborated further in the appendix.

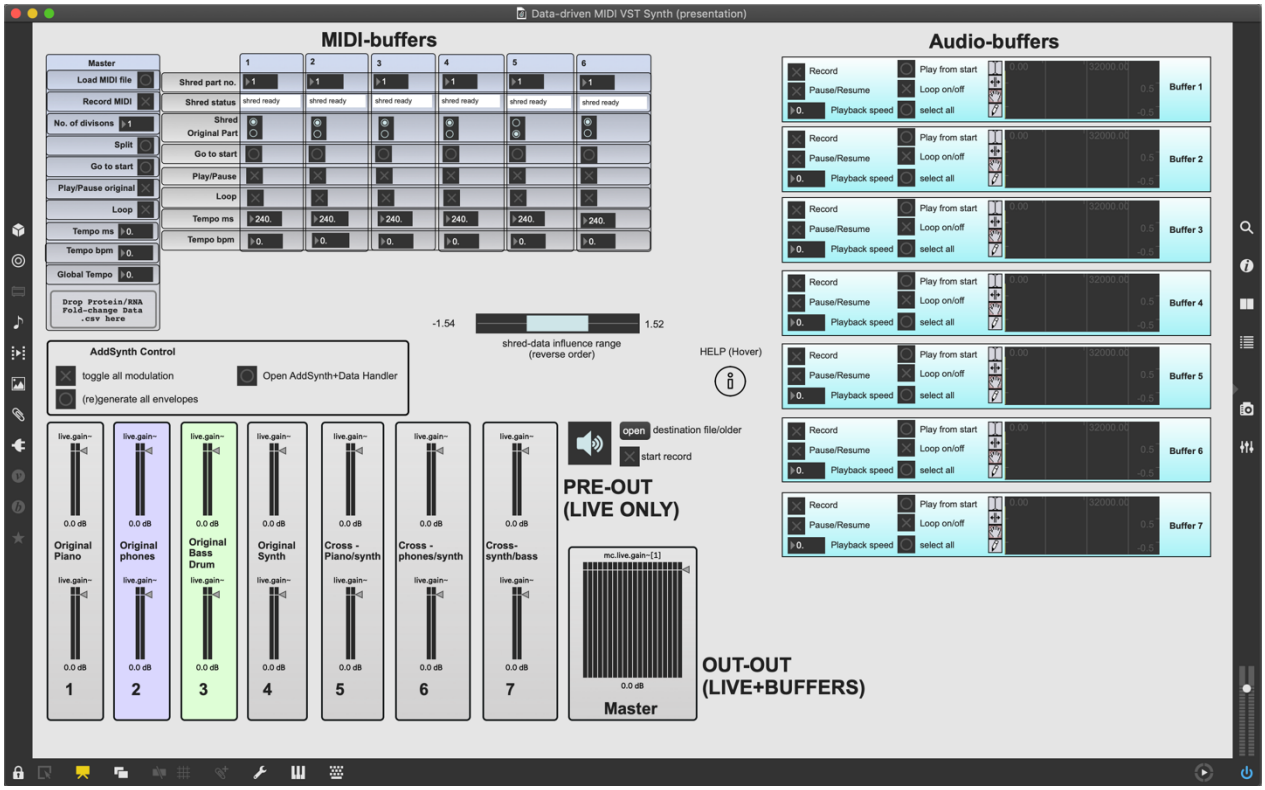



Figure 10. 1 – Data-driven, Midi VST Synth GUI

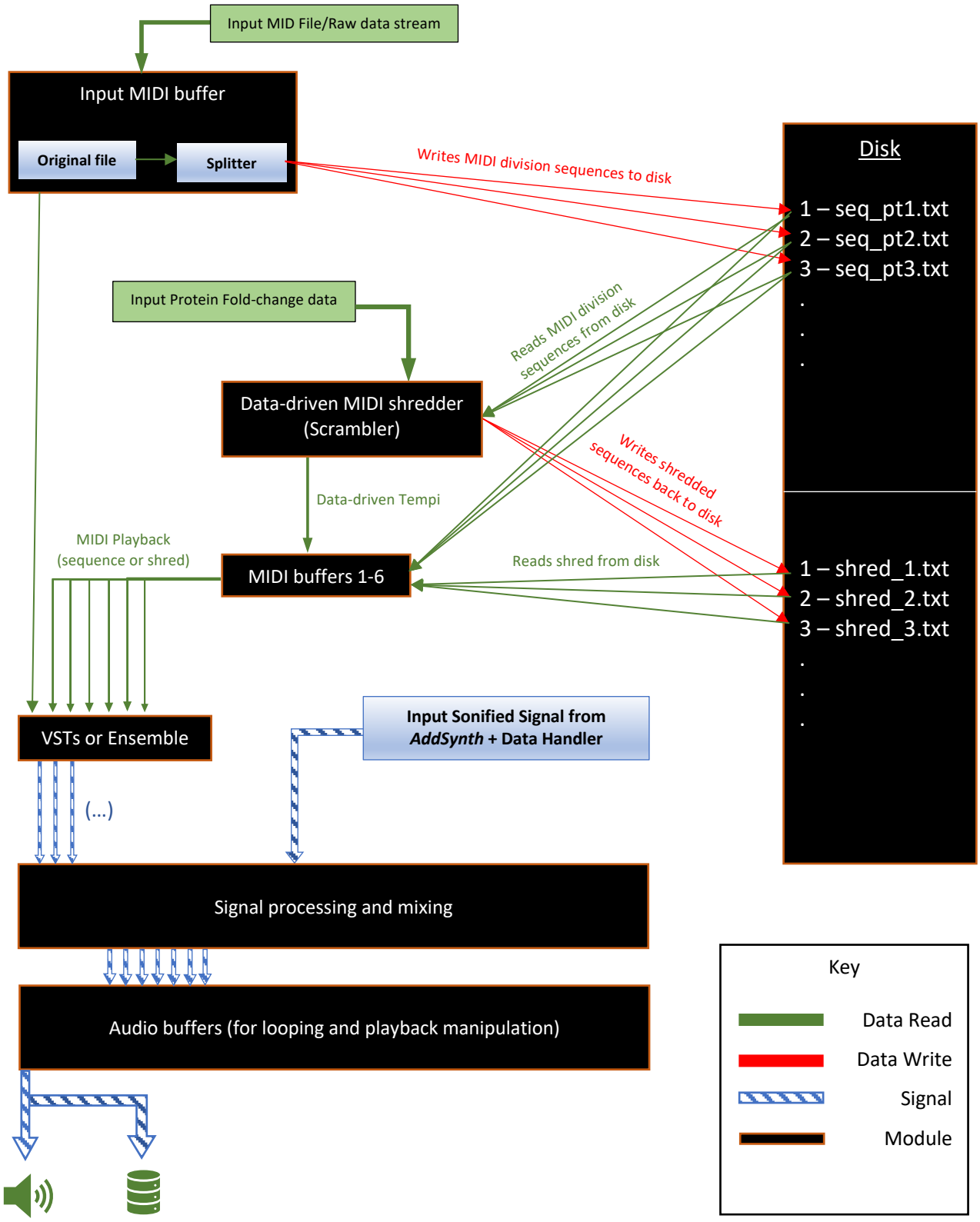



Figure 10. 2 – Data-driven MIDI VST Synth Design Diagram

## 10.3 Commentary

*Evading* was composed as I adopted another experimental approach towards allusive sonification in composition, with the particular use of instrumental sounds. Stylistically, it was inspired by and as a response to Karlheinz Stockhausen's *Kontakte (version Nr. 12½)*, for Piano, Percussions, and Electronics (Stockhausen, 1995). That is only in terms of its instrumentation and the overall timbral qualities of the sound world however, and it is perhaps all that it borrows from *Kontakte*, since this sound-world primarily serves as a bedrock for the exploration of elements of lyricism and dramatic composition in my own compositional language. *Evading* is also an attempt to allusively convey the narrative of one of the hallmarks of cancer, "Evading Growth Suppressors". This is attempted using various concepts abstracted from this hallmark's description to guide key metaphoric associations, between compositional and narrative elements, which are described further below.

To begin with, in order to implement the element of lyricism into the otherwise harsh and grotesque sound-world of pure-tone synthesis sonifications, I decided to look to my own instrumental music. Lyricism has been almost an inseparable part of my instrumental composition throughout the years. My tendency towards using linear progression (or melody) has always been an important feature of my practice, which has often served as a tool to convey a story or narrative over the course of the piece. This means having a clear start, finish and a sense of forward trajectory in time, while auditorily witnessing the unfolding of musical events as the story is being told. This lyricism perhaps also has roots in my cultural heritage as an Iranian, having Persian Folk/Traditional music as a constant while growing up. Melodic progression is one of the aspects of this music which is prominent in the foreground, and fundamental to its composition.

From a technical perspective, the inclusion of instrumental sounds in a data-dependent manner posed new challenges to deal with. Especially with my goal to incorporate a lyrical linear progression into the overall language. To tackle this, I created the *Data-driven, MIDI VST Synth* patch outlined above.

As demonstrated earlier in **Figure 10. 2**, this patch also works alongside the *AddSynth* module used in the composition of previous works. As pointed out, the main approach here is to manipulate input MIDI data (file) based on the protein fold-change dataset, through text-based scrambling of MIDI events. The resulting scrambled MIDI parts are then triggered automatically and also manually by myself, using the *Kontakte*-inspired ensemble of Piano, Vibraphone and Concert Bass Drum VSTs. In addition, pure tones generated by the parameter-mapping sonifications produced by *Data Handler* and *AddSynth*, are also put through multiple layers of a modified cross-synthesis technique that functions similar to convolution. The resulting effect can perhaps be described as a sort of 'spectral shadowing' between synthesis and instrumental material.

The source MIDI file used in this patch for the composition of *Evading* was an improvised, lyrical solo Piano piece titled *A Vicious Cycle*, composed and performed by myself. The original recording of this piece is included as part of the composition appendix. The most significant conceptual link between the composition of *A Vicious Cycle* and cancer is reflected in its title. The Vicious Cycle is cancer itself, caught in a never-ending, repeating cycle that changes but also deteriorates with every new iteration. The repetitive rising step rhythm on the bass throughout the piece was inspired by the shepherd tone and aims to hint at this cyclical nature. Also the harmonic language, while remaining fluid and going through modulations over different tonal centers, also broadly evolves according to the concept of a vicious cycle throughout the piece, ultimately landing in its most dissonant state in the final section. As this improvised piece was both lyrical and conceptually inspired by and about cancer, it seemed to be a suitable choice to experiment with using the patch. In other words, my aim was to capture the lyrical element of this piano piece, while also rendering it a data-dependent element to be used in conjunction with other sonified material in *Evading*.

### 10.3.1 Allusion to Hallmark of Cancer

*Evading Growth Suppressors*, is one of the hallmarks of cancer which outlines the cancer cell's ability to de-regulate the function and effect of powerful tumor suppressor genes. Many different genes have been observed to serve this purpose, out of which RB (Retinoblastoma-associated) and TP53 proteins are

considered bona-fide tumor suppressors. These intercept signals from extra- or intra-cellular origins and can in return trigger a stop to the cell's growth process or set the apoptotic programme in motion (RB mainly from outside the cell, TP53 from inside of the cell by detecting damage to the DNA). This polarity of 'outside' and 'inside' also bears a more obscure connection to the inclusion of instrumental sounds in contrast with synthesized pure-tone sounds.

Another notable growth suppression mechanism is what is known as 'contact inhibition'. Studies have shown that dense population of two-dimensional cell cultures, work towards inhibiting cell growth in vitro. Two exemplified players in this tumor suppression mechanism are the NF2 gene and the LKB1 protein. The product of the NF2 gene can couple cell-surface adhesion molecules to transmembrane tyrosine kinases. The result of this is an increase in the strength of the adhesivity of cell-to-cell attachments, which can also lead to limiting the reception of mitogenic signals. The LKB1 protein, responsible for "organizing epithelial structure" and "maintaining tissue integrity," is also known to be an important tumor suppressor which has the ability to cancel cell growth. This concept of 'contact inhibition' and its outlined mechanisms, i.e. exterior forces from other cells pushing and pressing on the cell resulting in the suppression of cancerous growth, bears another link to the spectral shadowing between electronic and instrumental sounds, especially in the way these two sound-worlds which independently refer to the inside (transmembrane tyrosine kinases) and outside ( cell-surface adhesion molecules) of the cell are also 'coupled', and interact sonically.

Primarily, from a textural perspective, the concepts of growth and suppression are represented in the use of constricted sounds, with suppressed high-end frequencies, which is a metaphor for the concept of (growth) suppression. The use of low-pass filter open/close motions, e.g. [1:09 - 1:53], and also utilizing the hiss noise in the background, e.g. [0:19 - 0:51], as a compositional element, are particular examples of the exploration of such sounds. To me, the ensemble broadly enacts what I imagined as the interception of growth suppressing signals by RB and TP53. The use of repetitive melodic figures on the Piano and Vibraphone which interject the pure tones in a rough, intermittent and pulse-like manner is an attempt at conveying the concept of signaling. In addition to this, in many occasions, the brighter pure

tones emerge from and pierce through the murky, claustrophobic textures, e.g. [2:31, 4:38, 5:56, etc.], which is a metaphor for the cancer cells' ability to evade growth suppression.

Having all the elements of the sound-world introduced at the start, and present throughout the work, links to the process of growth suppression being inherent to the cells themselves, as opposed to having it caused by an external entity. As it is the case generally with the hallmarks of cancer, tumors take advantage of and subvert these processes for their own malicious benefit. Therefore, I wanted to invoke senses of relentlessness and claustrophobia through the music. In terms of gestures, big crescendos and build-ups of texture and amplitude are more direct metaphorical links between cellular growth and sound. These gradual crescendo-ed, 'growth sections' all come to a halt (or drop), e.g. [3:08, 6:09 & 6:37], occasionally accompanied by a drum hit.

### 10.3.2 Retrospective

The use of instrumental parts, and also the fact that this piece's instrumentation was inspired by *Kontakte*, arises a valid question which is "why not have the instrumental parts performed live instead of using MIDI VST playback?". Unfortunately, due to the unforeseen circumstances caused by the outbreak of the coronavirus, especially regarding live performances, I was not able to properly explore this mode of performance for *Evading*. However, as pointed out earlier this in fact was one of the trajectories considered during the creation of the used patch, and the composition of this piece, and to this day remains an open path towards future exploration with this piece.

# Chapter 11:

# MUSICAL MODEL-BASED SONIFICATION OF PROTEIN FOLD-CHANGE DATA

## 11.1 Introduction

The largest body of technical programming work in this portfolio, this patch was designed with the specific intention of incorporating the model-based sonification technique in the process of sonifying protein fold-change data. The main reason for this decision was exploratory and experimental in terms of adopting an approach other than parameter-mapping, which is used with the other data-driven interfaces created in this PhD project. The resulting interface can be categorized as a 3D, multi-channel audiovisual instrument in the medium of electroacoustic/computer music. Details of its design, inspirations and implications, as well as relevant background research, are elaborated in an article authored by myself which was published and presented in the 2021 International Computer Music Conference (Mardakheh, 2021). What follows is a brief summary of the latter with quoted sections. The reader is encouraged to refer to the mentioned article – also included in the appendix – for access to the full scale of the work. **Figures 11. 1** and **11. 2** below demonstrate the main GUI of this interface which include the Control Window and Animation Window respectively.


Figure 11. 1 – Musical Model-based Sonification Control Window

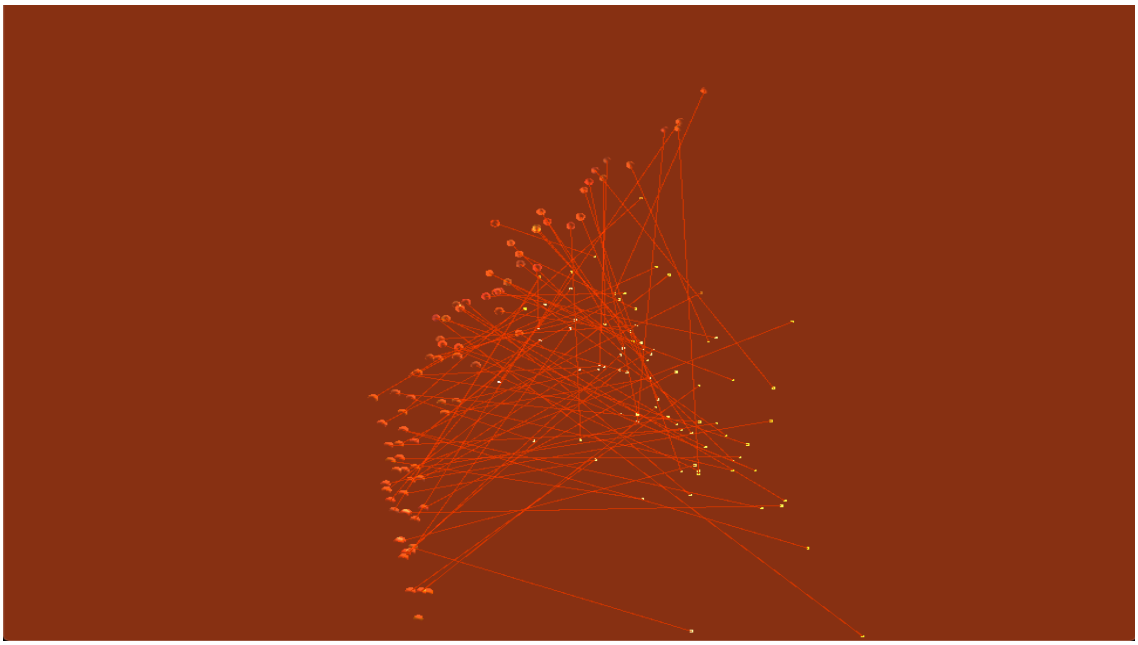


Figure 11. 2 – Musical Model-based Sonification Animation Window

## 11.2 Design

The intuitive and artistic design of this interface was adopted from and inspired by four exemplified sonification models found in various model-based sonification projects carried out by Thomas Hermann

et al. These are: the *Particle Trajectories in a Data Potential* (Hermann and Ritter, 1999), the *Data Sonogram* (Tunnermann and Hermann, 2009), the *Tangible Data Scanning* (Bovermann et al., 2006) and the *Principal Curve* (Hermann et al., 2000), sonification models. Further details regarding each can be found in the published article.

Another source of inspiration was the high-throughput protein fold-change data itself, a snippet of which can be seen in **Table 11. 1** below.

| Protein Index | 12hrs_Log2(Oncogene OFF/ON) | 24hrs_Log2(Oncogene OFF/ON) | 36hrs_Log2(Oncogene OFF/ON) | 48hrs_Log2(Oncogene OFF/ON) |
|---|---|---|---|---|
| **1** | 0.151547 | -1.10219 | 1.18763 | -0.86689 |
| **2** | -0.0507698 | -1.2263 | 0.733113 | -0.468267 |
| **3** | -0.0627022 | 1.2203 | 1.3548 | 0.887139 |
| **4** | 0.0158854 | -0.256123 | -0.835385 | -1.25104 |
| **5** | -0.148351 | -0.241301 | 0.468242 | 0.0580604 |
| **6** | 0.080265 | -0.790139 | 0.583954 | 0.0400841 |
| **7** | 0.378796 | -0.35472 | 2.02235 | -0.0973704 |
| **8** | 0.105474 | 0.485986 | -0.330463 | -0.0719597 |
| **9** | -0.328603 | -0.838825 | 0.169767 | 0.117093 |
| **10** | -0.162345 | 0.588433 | -1.26508 | -0.0670884 |
| **11** | 0.6496 | -1.35532 | 1.20024 | -0.361724 |
| **12** | 0.135667 | -0.294527 | 0.777793 | -0.287145 |
| **…** | … | … | … | … |
| **9524** | -0.113268 | 0.0206387 | -0.671347 | -0.205847 |

Table 11. 1 – Log2 Protein Fold-change Data in 12-48hrs Oncogene Removal Mass-spectrometry Analysis Experiment

To quote directly from the article:

> As with the broader context of Proteomics Analysis experiments and the mentioned produced datasets, the focus is to obtain a holistic image of all protein/RNA activity within the cell as it undergoes the transformation from a normal state to a malignant one. This is known as a *systems level understanding* of the biochemical processes within the cell (Mardakheh et al., 2017). Therefore, the use of an array of interconnected mass-spring systems, each element of which corresponds to each data point and in turn produces a distinct sonification on a discrete audio channel, seemed logical (Mardakheh, 2021).

Therefore, the adopted design of this model-based sonification instrument consists of two main parts:

1. An array of interconnected mass-spring systems in virtual 3D space which is the main point of gestural articulation of the sonification by the user (Red spheres in **Figure 11. 2**). Each mass-spring system produces an independent sonification on a discrete audio channel, contributing to a larger auditory gestalt.

2. A set of data points interspersed in the same 3D space alongside the mass-spring array, with each point corresponding to each mass-spring system (yellow dots in **Figure 11. 2**). The XYZ coordinates of these points are acquired using the hierarchical clustering of protein fold-change vectors from the source dataset, which is also a method commonly used by cancer scientists to reduce the high dimensionality and volume of the acquired fold-change measurements for ease in analysis (Beer et al., 2004). The one-to-one proximity relationship between each data point and its respective mass-spring systems is mapped to various synthesis parameters of the sonification of that particular data vector, i.e. that protein.

### 11.2.1 Synthesis

The main synthesis technique used here is "a modifiable granulation and micro-montage of a sample pool of any number of input audio files. The reason for this choice stems from the analogous relationship between the high-throughput dataset – which paints a holistic picture of the cell's protein activity – and the concept of the sound-object as a composite. This analogy is dominant in the choice of the concatenation of data-driven sound grains contributing to a broader auditory gestalt" (Mardakheh, 2021).

### 11.2.2 Mappings

The following quoted section features details of notable mappings which can be considered to encompass elements of curatorial sonification.

> […] The central tendency (Geometric Mean) of each protein, i.e. the activity level (up/down-regulation), is mapped to the ID of source audio files--effectively deciding which sound file goes into the source buffer of each granulizer. Therefore, by having an ordered set of distinguishable

sounds, for instance gamelan hits ordered in pitch from low to high, the resulting sonifications will sound low in pitch for less active and high for more active proteins. The central tendency parameter is also mapped to the ranges of *grain-generation* rate, *grain-transposition* and *grain-length* as well as the ranges of key physical parameters of the mass-spring array. Moreover, the amplitude envelope parameters of *decay, sustain and release* are mapped to the variable distance of each embedded data point to its respective mass-spring system. Meanwhile the *attack* and *grain generation rate* are mapped to velocity of the mass-spring systems. This ties the gestural and timbral qualities of each sonification to both the data and the human interaction element, which effectively also creates an intuitive and natural sound-world based on the physical aspects of sound and movement. I.e. when the mass-spring array is excited more intensely, the resulting sonifications will be louder and more granulized and when static, the sounds die out (Mardakheh, 2021).

More details regarding the operation, user interaction and other issues and implications related to using this interface can be found in the published article.

The sonified material produced by this instrument was used almost exclusively in the composition of the work titled *Immortality,* whose commentary follows in the next chapter.

# Chapter 12:

# (ENABLING REPLICATIVE) IMMORTALITY

## 12.1 Introduction

Tackling with musically getting across the various concepts pertaining to specific hallmarks of cancer, I decided to once again experiment with spoken words, with the particular aim of providing the context of the piece directly and literally to the listener, in order to achieve a more accessible listening experience. This was one of the main directives in the composition of *Immortality*, which explores the hallmark of cancer known as *Enabling Replicative Immortality*.

## 12.2 Commentary

Following the directive outlined above, I collected an interview with Professor Leonard Hayflick (Hayflick, 2011), in which he is discussing how he first established the concept of immortality in cancer cells vs. normal cells. Two selected sections from the latter interview were used as the main contextual narrative device in this piece.

The composition of *Immortality* was also an important exercise from a technical standpoint, as almost all of the sound material and its spatialization were acquired as a result of playing and improvising with the *Musical Model-based Sonification* instrument--elaborated in the previous section. The source audio files used in addition to the interview with Leonard Hayflick, were recorded Gamelan Hits, Data-driven synthesized tones generated by other patches (also used in other compositions), and two of my own previous compositions for solo Piano and solo Clarinet. The mentality behind this selection of source sounds was being varied, inclusive and unbiased, in terms of sound sources. This musically unbiased attitude points back to the impartial nature of cancer, which does not discriminate either in the macro nor the micro level. In addition, the choice of using my own previous instrumental compositions also touches on the concept of replicative immortality. Like various different types of cells which become immortalized and end up serving a different malignant purpose, granulized and micro elements

(motifs/chords/rhythm) from these compositions are used in the same sense that they are being infinitely replicated, morphing into distinctive musical entities, which serve a completely different purpose compared to what they were originally created for.

The concept of cell Immortality stems from the contrasting behavior of normal and cancerous cells, in terms of their mitosis. As pointed out earlier, normal cells only go through a limited number of growth-and-division cycles, before entering a non-proliferative, metabolically active state known as *Senescence*, which is followed by *Apoptosis* (Cell death). As it has been observed, cancer cells have the ability to circumvent the natural defense of this limitation, and as a result can enter an unlimited number of growth-and-division cycles. In other words, they can cheat death and become immortal.

The culprit for this is identified as "*Telomerase, the specialized DNA polymerase that adds telomere repeat segments to the ends of telomeric DNA"* (Hanahan and Weinberg, 2011). These telomere repeat segments essentially protect the ends of chromosomes. As normal cells go through multiple growth-and-division cycles, the length of the telomeric DNA shortens significantly, resulting in a lack of protection of the said chromosomes, and giving way to the end-to-end fusions of the chromosomal DNAs, which damage cell viability and would eventually trigger senescence and apoptosis. This is the point of origin of the hard-wired limitation on the number of growth-and-division cycles of normal cells. In contrast, scientists have observed that telomerase is expressed at significant levels in the vast majority of immortalized (tumor) cells, thereby concluding the correlation between the length of the telomeric DNA, and the resistance to senescence and apoptosis. In other words, cancer cells resist the latter barriers and become immortalized by avoiding telomere erosion during growth and division.

One of the most important concepts which is emphasized throughout this piece is *repetition*. This repetition is a metaphor for both the broad concept of replicative immortality, and the more specific function of the telomerase, i.e. adding telomere repeat segments to the telomeric DNA. This is implied in the repetitive nature of the granulation and micro-montage processes imposed on the various source sounds used, i.e. Gamelan hits, speech fragments, various motifs on the Piano and Clarinet. More strikingly is the almost emphatic use of tremolos in the second section of the work [3:52 - 6:40]**.** The

inherent repetition embedded within the tremolo gesture makes it a very suitable metaphorical musical element for the purpose of conveying the sense of continuous replication to the listener. These ominous-sounding tremolos vary in pitch, length and pace, representing the varying length of the telomeric DNA, shortening or extending. Telomerase – especially its protein subunit TERT – has also been observed to be (among other *noncanonical* functions) associated with enhancing cell proliferation, separate to maintaining the length of the telomeric DNA, which ties it to *Sustaining (proliferative signaling)*. The common use of vocal granulation in both these two works, and the emphasis on the use of fragmented speech as a narrative device (whether sparsely layered and partially intelligible or unintelligible and granular) stylistically connotes this connection. Also, another common sonic element between this piece and the previous hallmark compositions is the accented bass-drum hits, which, in addition to signifying the programmatic biochemical processes within the cell, serve as a signature gesture in my compositional language in this portfolio.

As an Ambisonic piece, *Immortality* primarily explores space in a composerly and allusive manner, as opposed to indeterminate. Examples of this are 1) the repeating motions of both the speech mass and the foreshadowed tremolos, from the rim of the dome to the center and back, while also simultaneously moving towards the zenith and nadir positions within the dome [1:45 - 2:10]**;** and 2) the spatial journey of the gong hit and its stretched, distorted resonance, which start from the front-center position and end at rear-center [2:53 - 4:05]; or 3) the circular motion of the high-frequency synths around the rim of the dome, from the rear to the front and back [4:53 - 5:42]. However, as the model-based sonification patch already produces spatialized material due to the performer's interaction with the instrument, the composerly control imposed on spatialization in this work is not all encompassing. In fact, some of the mentioned raw material's spatial elements are kept intact. Examples of this are the granular masses of sound, e.g. the high Gamelan hits [0:00 - 2:38]**,** some of the speech fragments [1:45 - 2:13], and also the instrumental tremolos [4:32 - 6:32], whose controlled spatialization happens at a broader level and applies to the masses as a whole. On a metaphorical level this obscurely implies the spatial dislocation of immortalized cancerous growth, or Metastasis, i.e. the invasion of cancer growth to near and distant tissue (which is further explored in the final, audiovisual work in this portfolio, Chapter 15).

To me *Immortality* is perhaps a rather formalistic and dramatized lesson. This lesson is of a tertiary form, wrapped by the narrative of Hayflick, and takes the listener on a dramatic sonic journey inspired by and based on the inner workings of the process of cell immortalization. The Gong hits signal the end of each narrated section or part of the 'lesson' [2:53 & 7:49], and the 'optimistic' sounding harmony of the drone beneath the brittle texture of the granular gamelan hits at [0:00 – 1:33]**,** echoed at [6:49 - 7:40], reflect a sense of enthusiasm, positivity, or even clarity, which pertains to my own personal optimism about science in general. This is contrasted by the darker and more ambiguous harmony of the middle section [3:52 - 6:40], which sets the expectation and remains on the edge of harmonic progression, but never actually does so. Instead, the gestures there multiply spatially and repeat, which again points back to the concept of replicative immortality. The resulting ambiguity that flows through to the listener is also yet another analogical take on the uncertainty surrounding cancer itself, whether in terms of its diagnosis or our still limited understanding of its biochemical makeup.

# Chapter 13:

# MALIGNANT GRAINS – IMPROVISED PERFORMANCE

## 13.1 Introduction

*Malignant Grains* is another instance of a *Generative* approach towards sonification for composition and live performance in this portfolio (in addition to *Hours of Oncogene*). This work is a live, improvised performance using solely the concatenative synthesis (cataRT) of sonified material previously produced by the *Data Handler, AddSynth, Data-driven, MIDI VST Synth* and the *Musical Model-based Sonification of Protein Fold-change Data* patches.

## 13.2 Commentary

The main reason for the use of sonification being categorized as *Generative* in this piece, is the full control of the performer in manipulating control parameters of the concatenative synthesis. Even though the raw material used was generated by the *Allusive* and *Curatorial* sonification of data, using the patches mentioned above, these sounds are deconstructed into grains, concatenated and iterated according to various parameters controlled during the performance. Therefore this work is mainly an exploration of the capabilities of cataRT, through which the inherent, hidden sonic potential of the previously produced sonifications can be unlocked.

However, there are still a few performance choices which are not entirely devoid of connection to the concept of cancer, and align with the broad compositional language of this portfolio. For instance the overall choice of abrasive textures, exploring the extremities of pitch/frequency or the sudden and surprising breaks or leaps in control parameters, all point back to the malicious and grotesque nature of the context of the piece, i.e. cancer. In addition, the concept of expansion and growth from a seemingly harmless and miniscule entity into a much larger and malevolent granular mass, is represented in the transformation of the short-attack, crackling grains into rich and polyphonic drones. This is an *allusive* compositional decision and remains constant through different performances.

What highlights this piece, which is also the reason for its inclusion in this portfolio, is the fact that it served as a precursor to *Malignant Angiogenesis*. Another improvised piece in this portfolio, which explores the interplay between data-driven and composer-driven events in live improvisation. In other words, *Malignant Grains* is in many ways an independent study for the latter work.

From a technical standpoint, the performance interface of this piece, and also *Malignant Angiogenesis*, are very similar. This interface consists of the mouse, keyboard, and a midi-controller – featuring faders and buttons – which is mapped to various control parameters of cataRT, e.g. grain rate, grain size, grain crossfade time, attack, release, gain, and stereo diffusion. During performance, the keyboard is rarely used, and the mouse and the midi-controller take on the most responsibility.

As an instrument, cataRT is very versatile, and has the capability of producing a wide variety of textural and gestural material, which is the main reason for its choice as the sole instrument for improvisation. As pointed out earlier in Chapter 5, textural changes are mainly the result of changes in the control parameters, which are mapped to the faders. Meanwhile, gestures are produced by the movement of the cursor (either data-driven or manual, using the mouse) on the corpus grain display. In other words, the mouse hand controls gestural articulation, while the fader hand controls texture. This set up requires more dexterity on the mouse hand compared to the fader hand, and also limits the number of faders that can be manipulated simultaneously.

The recorded performance included in this portfolio is one instance of improvisation with this interface. The resulting piece is spectral and structurally sectional, with a rounded overall form. The narrative is a journey through various sound-worlds, which in my mind metaphorically represent the various hallmarks of cancer. They are a fantastical account of what it would sound like to 'fly' through the cell's nucleus and sonically witness its environment at various stages of cancer. It should be nonetheless pointed out that this narrative was dominant only in this recorded performance, and other iterations or performances can explore and produce almost entirely different concepts and results. This is evident in *Malignant Angiogenesis*, which incorporates a more developed version of this performance interface and explores different conceptual and musical narratives.

# Chapter 14:

# MALIGNANT ANGIOGENESIS – PATCH & IMPROVISED AUDIOVISUAL PERFORMANCE

## 14.1 Introduction

This chapter features a brief overview of the *Data-driven/Audio-reactive Animation* Max patch, followed by commentary on the live-improvised performance titled *Malignant Angiogenesis*, which was realized using the latter patch, alongside the *Modified Data-driven cataRT.*

## 14.2 Data-driven/Audio-reactive Animation Patch

The main aim in designing this patch can be summarized as creating a data-driven and audio-reactive interface for producing live visuals for the improvised performances of the work *Malignant Angiogenesis*. While this interface can be operated manually using a number of user-driven, modifiable parameters similar to other live improvisation interfaces in this project, its design bears a specific focus on audio-reactive and autonomously directed and edited visuals, which would eliminate any need to be operated by a performer. The latter design also results in partially stochastic visuals which can vary based on the sonic characteristics of the improvised performance, as well as the input protein data.

This patch was my first formal attempt at animation programming using OpenGL in Max/MSP – which jit.gl objects interface (Max Online Documentation, n.d.) – and it was created as part of a collaboration with the Iranian visual artist, Ehsan Hemmati-Faräz. The primary idea behind this collaboration, which consequently shaped the design of this patch, was to combine and juxtapose fixed (pre-rendered), hand-drawn animation sequences by Ehsan, with the live, audio-reactive, 3D animations produced by jit.gl objects in this patch. **Figure 14. 1** demonstrates the (reduced) GUI of this patch. For a detailed look at its programming, please refer to the appendix or the patch itself. More details regarding aesthetic and conceptual aspects of the resulting visuals can be found further below in this chapter.

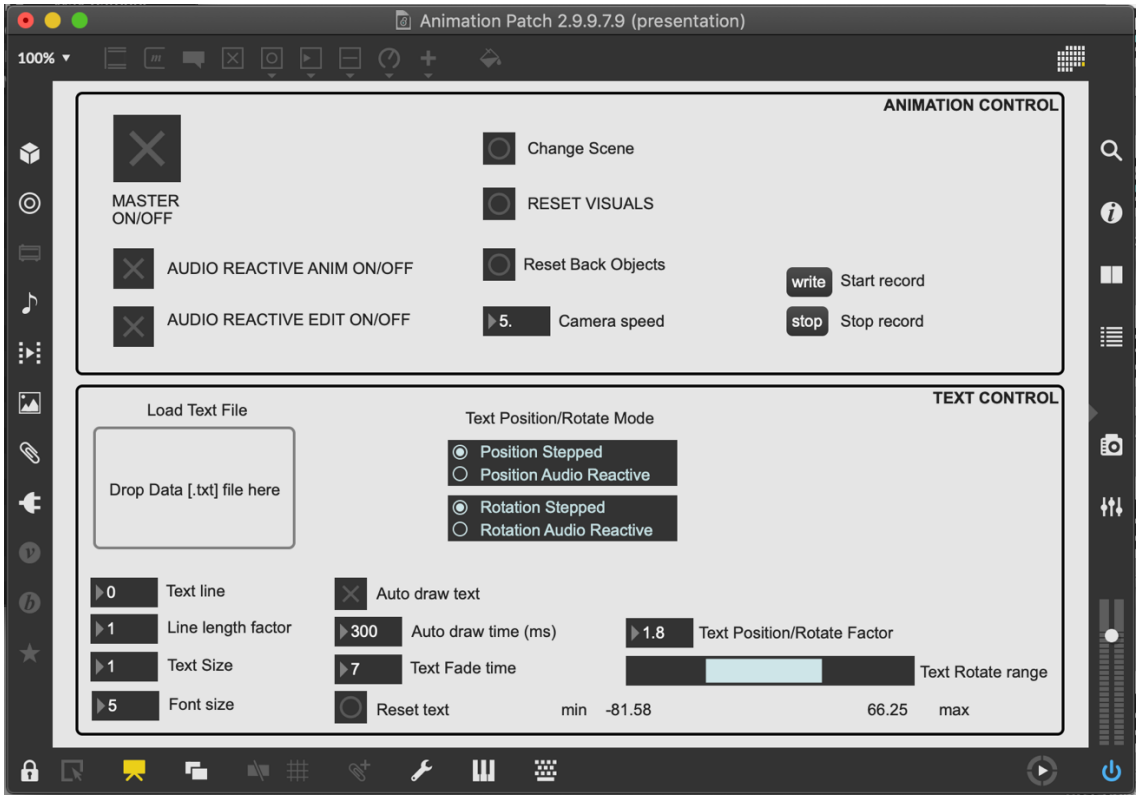



Figure 14. 1 – Data-driven/Audio-reactive Animation Patch GUI

The resulting visuals achieved using this patch can be examined in the screenshot provided in **Figures 14. 2** and **14. 3** below. For the full result, please refer to the live-improvised audiovisual work, *Malignant Angiogenesis*, whose commentary follows in the next section.

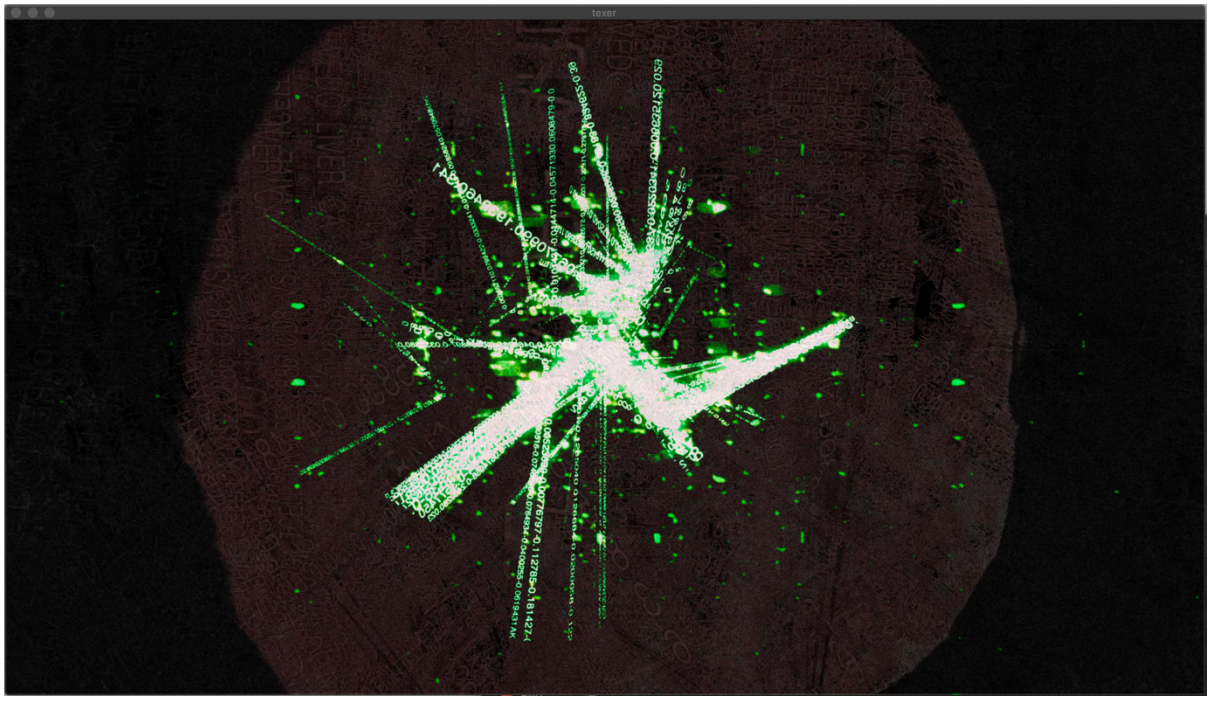


Figure 14. 2 – Produced Data-driven/Audio-reactive Animations (1)

Figure 14. 3 – Produced Data-driven/Audio-reactive Animations (2)

## 14.3 Commentary

*Malignant Angiogenesis* is the work in succession after *Malignant Grains,* focusing on live improvised performance featuring a mix of data-driven and performer-driven control exercised over concatenative synthesis. In addition, this work also features real-time, audio-reactive visuals which were designed and implemented in Max/MSP, specifically for varied improvised performance durations. These visuals were produced through collaboration between myself and Iranian visual artist, Ehsan Hemmati-Faräz, and consist of real-time 3D-rendered text elements (displaying rows of the used dataset in the sonification) and pre-rendered, abstract, hand drawn sequences (minimalistically portraying the process of cell proliferation, tumor progression and Angiogenesis). The inclusion of the data itself as text within the rendered visuals was inspired by Ryoji Ikeda's *Datamatics*, in which various datatypes are sonified and materialized in various formats, i.e. audiovisual concerts and installations (Ikeda, 2006). The separation of these visuals in dimensions and style highlights the data driven nature of the work.

The live render of the visuals is mostly directed by a combination of data-driven and audio-reactive cues during the performance. The pre-rendered animations are triggered as autonomous cutscenes, reacting to the performer's improvisation--both spectrally and gesturally--and depart from, or return back to the real-time, text-based, audio-reactive elements. There is however the possibility of exerting more manual directional control before the performance with minor patch modification. The pre-rendered animations also carry the abstract narrative of the work, which is derived from the process of inducing angiogenesis in cancer cells.

Angiogenesis can be summarized as the cancer cells' ability to constantly form blood vessels around tumors (even early on at a microscopic state) to supply them with nutrients, and extract metabolic waste. This process occurs commonly and naturally in the body, i.e. the angiogenetic switch can be turned on and off during normal tissue-related processes such as the healing of wounds and female menstrual cycling. However, in tumorigenesis, this switch is chronically on, resulting in the "birth of new endothelial cells and their assembly into tubes, in addition to the sprouting of new vessels from existing ones*".* Similar to other hallmarks, research has shown that the angiogenetic switch is controlled by

counterbalancing genes, prototypically inducers such as vascular endothelial growth factor-A (VEGF-A), and inhibitors such as thrombospondin-1 (TSP-1). VEGF-A expression has been observed to be controlled and upregulated by certain oncogenes, such as *Ras* and *Myc.* The blood vessels formed by *Malignant Angiogenesis* are described as "typically aberrant", featuring characteristics such as "precocious capillary sprouting, convoluted and excessive vessel branching, distorted and enlarged vessels, erratic blood flow, micro-hemorrhaging, leakiness and abnormal levels of endothelial cell proliferation and apoptosis". Some of these adjectives and descriptions are metaphorically alluded to in this piece, which is explained further below.

Abstract references to 'cells' and 'blood vessels' are implied in the use of simple geometrical shapes, i.e. circles and lines respectively. These elements are used in both of the pre-rendered and real-time scenes. In addition, further references to the antiquity of cancer are embedded in some of the pre-rendered cutscenes, through symbolism in both color and shape. These nod to Hippocrates (460-370 BC), to whom the origin of the word '*cancer'*– a growth resembling a crab with attached blood vessels for its claws, latching onto the body (The American Cancer Society, 2018) – is attributed. Moreover, Ibn Sina's description of cancerous growth is referenced, as is what he thought to be the substance responsible for causing cancer (he described it as 'burnt bile', which is represented in the animations with colors matching various shades of the bile color, see Book 4 of The Canon of Medicine, originally published in the 11$^{th}$ century (Avicenna, 2014).

As mentioned earlier, the musical element of this work's performance interface, is an upgraded version of the interface used in *Malignant Grains*. This means that the synthesis module utilized is once again, cataRT. However, the most significant change here is the modification made on cataRT which allows the automatic, data-driven gestural articulation of sound grains, as opposed to being performer-driven. In fact, exploring the balance between performer-driven and data-driven gestures is one of the main compositional goals in this work. As indicated earlier in *Malignant Grains*, this gestural articulation in cataRT is produced by the movement of the mouse cursor in the 3-dimmensional grain display (X/Y/Color). To control this using the data, each protein's fold-change data vector is mapped and

translated into a 2-dimmensional XY vector that controls the display cursor, and subsequently plays various grains it passes over. Moreover, the time over which each vector is translated into two-dimensional space is mapped to the central tendency (geometric mean) of that protein, i.e. the more active proteins with higher central tendencies will take longer to complete their vectorial trajectory of the cursor. However, to exercise manual control, the overall length of each vectorial trajectory can also be more broadly modified by the user during performance. Also, the magnitude of the mapping (min/max ranges) between data vectors and XY gestural vectors can be modified by the user. This means the performer can limit the unfolding of the cursor trajectory to a narrow section of the grain display, producing as a result sounds that have similar textural characteristics. In addition, similar to *Malignant Grains*, other parameters of the synthesis are also controlled by the performer, via the MIDI controller faders, knobs and buttons. Using these tools, this improvisation interface is essentially focused on achieving a combination of determinate and indeterminate musical elements, exploring the musical dialogue that arises between data-driven and performer-driven components.

The sound-world of this piece features two main elements: a rhythmic, pitch-based bass figure, and overlaid granular textural material. The relentless motion of the rhythmic bass connotes and alludes back to the movement of blood cells through vessels and capillaries – which often can be seen to have blood cells move through them in single file. Another source of inspiration for the latter was actual microscopic imagery of blood moving through vessels (Stammers, n.d.). This bass rhythm is constant and present throughout each section, while also having an erratic and jittery behavior. This alludes to the nature of blood flow in tumor blood vessels pointed out earlier, and also lays a musical foundation for the improvised textural elements in the foreground. In addition, while the bass figure is rooted firmly in B, harmony throughout this piece is treated in an ambiguous and dissonant manner, similarly to other pieces in this portfolio. This ambiguous (and grotesque) element alludes to the “aberrant” nature of tumor blood vessels. Nevertheless, there are also occasions where tonal consonance is vaguely implied, e.g. [7:11 – 8:26] in the included performance. In addition, the “leakiness” and “micro hemorrhaging” of tumor vasculature are more obscurely alluded to by the inclusion of transposed, high-pass filtered

samples of the same rhythmic bass figure which connotes erratic blood flow ([2:57 - 3:38] & [3:59 - 4:42]).

One of the notable challenges with this setup, and perhaps with improvisation in general, was maintaining a coherent form and duration. Working with this interface, I have often found it easy enough to lose track of time and end up playing for extended durations. This problem is exacerbated in the case of this piece in particular, as there is also a visual element, which plays the role of the allusive narrative device via the intermittent appearance of pre-rendered animations. Even though the visuals are directed by data-driven and audio-reactive cues specific to each performance, longer plays will inevitably have these loop around due to the limited number of the pre-rendered animations. This causes the narrative to lose its linear direction from start to finish. To tackle this, I decided to impose a predefined, twofold structure onto the piece. The resulting two sections are delineated by a noticeable change in the pace of the rhythmic bass (in the case of the included performance at [approx. 6:34]: double-time tempo, though this can vary in different iterations). This twofold structure makes it easier to maintain the overall form, and to keep the visual narrative consistent. Additionally, it allows for free-form improvisation to take place in the form of textural and gestural elements in the foreground within each section.

# Chapter 15:

# EMERGE>CONSUME>DEPART (METASTASIS) – PATCH & IMPROVISED AUDIOVISUAL PERFORMANCE

## 15.1 Introduction

This chapter features a brief overview of the *Data-driven Ambisonic Spatializer and Make Noise Modular-Synth Modulator* Max patch, followed by commentary on the live-improvised audiovisual performance titled *emerge>consume>depart (Metastasis)*, which was realized using the latter patch, alongside the *Make Noise Tape & Microsound Music Machine* and the *Modified Data-driven cataRT.*

## 15.2 Data-driven Ambisonic Spatializer and Make Noise Modular-Synth Modulator

This patch was created as yet another live improvisation performance interface with the specific intention to spatialize and modulate the output of the Make Noise Tape & Microsound Music Machine (Make Noise, n.d.). In the closing months of my PhD project, I started experimenting with and improvising on the department's new Make Noise modular synth. The sonic complexity of its high-fidelity output and its flexibility as an instrument immediately piqued my interest. However, while capable of producing such intriguing and complex sonorities and stochastic patterns, the Tape & Microsound Music Machine's output is strictly stereo without any form of built-in modifiable panning. Furthermore, its stochastic behavior is independent and unrelated to the Protein Fold-change datasets used in this project. Therefore I set out to expand and augment it, in order to not only modulate its synthesis parameters using data-driven control voltages, but also spatialize its output, in a data-driven manner. The resulting patch is one that effectively carries out both these tasks and is further elaborated below. **Figure 15. 1** demonstrates the main GUI of the patch.

In addition to the modulation and spatialization of the Make Noise output signal, this patch also operates in conjunction with the *Modified, Data-driven cataRT*, elaborated earlier, and takes the produced stereo signal from cataRT as input, in addition to that of the Tape & Microsound Music Machine. This is done so

with the intention of maintaining aesthetic consistency in my own improvisation practice within this project, essentially bringing these two interfaces (instruments) created specifically for live improvisation together.

The spatialization is implemented using IRCAM's Spat (version 5) Max/MSP library (Ircam, 2018), which is a required external dependency to run this patch. The Spat library is a very practical and convenient tool as it features a broad range of Max objects for real-time spatialization, composition, post-production and live performance. Moreover, it supports a wide range of panning and spatialization modes, e.g. Angular, Binaural, VBAP (2D/3D), VBIP (2D/3D), HOA (2D/3D), etc. and also operates using the Open Sound Control (OSC) protocol which together make it a suitable and highly-compatible choice for adapting to various performance settings and PA systems. The spatialization type used in the current version of the patch is 3D Higher-Order Ambisonics (HOA3D). A reduced stereo version was also created using VBAP, and effectively utilized for live performance on one occasion. Spat objects are highlighted with the color green in **Figure 15. 1**. Further implementation details regarding this patch can be found in the appendix.

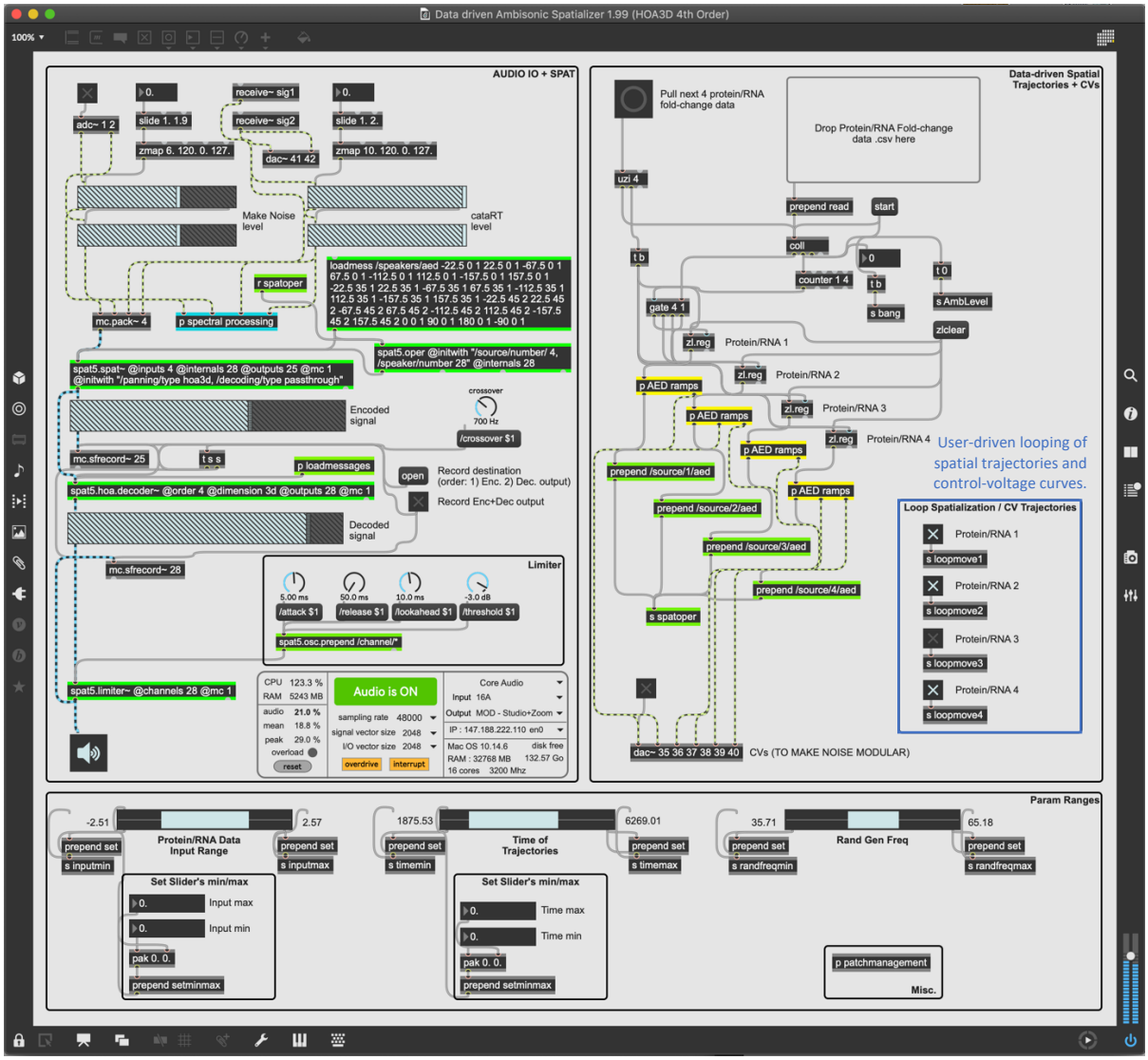



Figure 15. 1 – Data-driven Ambisonic Spatializer & Make Noise Modulator GUI

### 15.2.1 Operation and Performance

As mentioned earlier, this patch runs together with the *Modified Data-driven cataRT* and together with the Make Noise modular synth, essentially serve as an expansion to the data-driven improvisation interfaces created in this project. This expanded version also consists of two external MIDI controllers, the ICON Platform-M (used with cataRT before) for textural manipulation, and the Behringer FCB-1010 MIDI Foot Controller (Music Tribe Global Brands Ltd., n.d.) mainly used for manipulating signal levels and trigging the looping of control-voltage curves and spatial trajectories. As a performance interface, its particular design and the combination of user-driven and data-driven controls bears the aim of reaching a

balancing between the two during improvisation. The following audiovisual piece was realized using this performance interface and is elaborated below.

## 15.3 Commentary

As the final piece in this portfolio, *emerge>consume>depart (Metastasis)* focuses on alluding to cancer cells' capability to invade neighboring and distant tissue, i.e. Metastasis, through an abstract, live-improvised, audiovisual performance. As Hanahan and Weinberg point out, the mechanisms responsible for activating this cancerous invasion are yet largely unknown, although thanks to accelerated research in recent years cancer scientists have managed to learn a great deal about the complex multifaceted process of metastasis. One of the key alterations at the cellular level implicated in metastasis is the change in cancer cells' shape and also the way they are attached to "other cells and the extracellular matrix (ECM)". This involves two carcinoma cells, E-cadherin and N-cadherin. The former is an important "cell-to-cell **adhesion** molecule" which allows the forming of epithelial cell sheets and "maintaining the quiescence of the cells within these sheets". Research has revealed that cancer cells induce a loss of this key element, allowing their invasion into neighboring and subsequently distant tissues. On the other hand, N-cadherin which is expressed in migrating neurons and cell embryos during the formation of organs, has been observed to be increased (Hanahan and Weinberg, 2011). Such alterations are widely attributed to a regulatory programme known as "epithelial-mesenchymal transition (EMT)", which is affected by a variety of different biochemical factors. However, the latter does not bear going into as allusive references to these complex cellular processes in this short audiovisual piece are kept at a simple level, in favor of sonic complexity and musical effectiveness.

The key takes from the above paragraph were the concepts of adhesivity and plasticity, which informed some of the textural qualities of the sounds, and which can be considered as an important allusive element in the use of pitch-shifted, popping and bubble-like sounds. Moreover, the sound-world of this work is strikingly hectic and chaotic, featuring a wide variety of textural and vocal sonorities which are more or less constantly present and in motion. While research has shown that metastasis can in fact happen remarkably early on, the predominant belief is that the term pertains to a late-stage

development in cancer as a disease. This ‘lateness’ is the main reason for the abrupt start of the piece, as well as its busy and chaotic sound-world. In addition, this chaotic sound-world and its sonic variety also signifies the affected tissues during metastasis, which depending on their location in the body can consist of a wide variety of different types of cells.

As its title reflects, the main musical idea in this piece is the emergence of a relentless and repetitive, pitch-based sound-object which is juxtaposed, and in constant struggle with the other chaotic textural sounds. This is essentially a fast-paced, stochastically-expressed tremolo which signifies and alludes to metastasis. Harmonically, the latter can be identified as an (F-Major add $4^{th}$ chord: F + A + $B_{\flat}$ + C), whose

tones alternate constantly between these pitches in random order. This tremolo **emerges** through the textural sound-world (of the affected tissue) over the course of the piece (e.g. at [1:10, 1:46, 2:33, etc.]), finally **consuming** it having spread its malignancy (at [3:45] ), and **departing** to affect another tissue in the body.

One of the main elements under exploration in this piece is space. As an allusive element in my mind, the exploration of space through the data-driven spatialization of sounds, as well as the particular use of reverb, bears a key reference to metastasis itself, i.e. the cancer cells’ ability to literally 'move’ in space and spread throughout the body. This allusive link was also one of the more abstract and conceptual reasons for designing the *Data-driven Ambisonic Spatializer and Make Noise Modular-Synth Modulator*, in addition to its technical benefit in spatializing the static and stereo-only output of the modular synth. While the included performance is a binaural mixdown, as an Ambisonic piece this improvised performance is compatible with and intended for larger, multichannel speaker layouts which would create a more effective listening experience. As mentioned, the use of vast reverberance and feedback, i.e. at [2:03–2:16] and the closing at [4:00–4:44], aims to highlight this allusive link further. Finally, another element that reinforces and highlights the relevance of the concept of ‘spatial motion’ here is the constant zooming-in/out motion within the abstract visuals. The apex of this motion in particular is the exaggerated zooming-out at [2:03], which takes place in conjunction with the dramatic increase in reverb.

Lastly, the visuals are the result of further exploration of animation programming using OpenGL objects in Max/MSP by myself. These were achieved using audio-reactive manipulation of the recorded video from my improvised performance of the piece, combined with generative noise textures (jit.gl.bfg object) and custom-made shaders. Apart from the zooming-in/out motion mentioned above, the imposition of generative noise textures onto the performance video in itself is yet another, more obscure reference to metastasis. What is intended is that these textures also spread onto and invade the 'normal' recorded video, similar to what metastatic cancer does to normal cells.

# CONCLUSION

One of the things I have learnt throughout my research has been that as an artist and composer, my approach towards data sonification--and by extension, all music composed in the realm of Science-Art--is most influenced by factors and stimuli which are *external* to the science: namely, the data and its context. Even though the framing and objective of the produced works can be justified by and serve the scientific context behind the data, the 'how' of the creation of these pieces, especially where emotional and aesthetic choices are concerned, is also significantly influenced by my background as a musician and my state of mind and emotions. The latter has been inevitably impacted by many personal experiences and encounters throughout the past 4 years, such as the news of my father's cancer diagnosis in 2019, or the effects of isolation during the outbreak of the COVID 19 pandemic. As an artist, I believe that both the conceptual depth and the aesthetic choices within the pieces elaborated in this commentary have come as a result of my attempt to frame these experiences--whether personal or professional, related or unrelated to cancer--within the context of my research. In other words, they have been attempts to see and make sense of these events through the scope of the Hallmarks of Cancer: to 'live' the project on a more personal and deeper level, rather than ticking boxes to complete it. As a composer, I believe I have always had the tendency to engage and grapple with my work on such a personal level, which I have always considered as both a blessing and a curse.

Referring back to the Strata-based classifications, an *Allusive* approach towards data sonification is one that allows for such a personal and emotional perspective on the science behind the resulting works. It maintains the scientific 'scaffold' while also permitting more freedom of expression to the artist. As pointed out earlier, this pushes such works into the realm of outreach activities, aiming also to promote the status of the underlying scientific field in some capacity. Depending on the desired effect or goal of the outreach effort and the consideration of its target audience, works can take any shape and encompass a variety of levels of abstraction or obscure connections between the 'science' and the 'art'. In my experience, implementing these abstract, allusive connections and writing music the way I have

and continue to learn to do throughout my career as a composer to this day required constantly maintaining a dual musical and scientific perspective, which I found can be rather tricky.

Looking at the work of other practitioners in the field, i.e. composer-sonifiers, this dual perspective can also be observed. For instance, Carla Scaletti uses the 'hat' metaphor to explain and perhaps justify her use of sonified material in her composition in laymen's terms. She points out that when she is designing auditory displays, i.e. adopting a *Curatorial* approach, she puts on her 'sonification hat'; and when she is writing a piece of music with sonified material, she wears her 'composer hat' (Scaletti, 2013). Such a metaphor seems to be highlighting the difference between a strictly *Curatorial* approach, and an *Allusive* or *Generative* one. However, while Scaletti seems to suggest that these approaches are and should be distinct, the boundary between them is not clear-cut and they can indeed overlap.

Another example of such a reference, which aligns with the above point, is Mark Ballora's insight and reflection onto his own work, especially with regard to its reception by different audiences:

> At the International Conference of Auditory Display at Michigan Technological University, participants engaged in spirited discussions of the ways musicality may detract from transparency, adaptability and verifiability. Days later, […] I presented sonifications about the ocean, stressing that they had been created with attention to the very issues that had been the subject of concern in the previous session. Yet I was not entirely congratulated for it. My collaborator asked me to remove a key informative indicator (a series of beats describing depth), which they found distracting; and a member of the steering committee remarked that, while the work seemed well-intentioned, the goal of the grant was to change hearts and minds about ocean health, and simply creating an alternative form of graphing was unlikely to create this effect (Ballora, 2021).

What Ballora goes onto conclude from this experience is perhaps what captures the essence of and reason for my *Allusive* approach towards data sonification in this PhD project:

> I had to concede that he had made a good point, and it was a valuable wake-up call: My focus in this work had drifted from my original, artistic-based intentions, and this was to the detriment of the work, despite what other more pragmatically minded colleagues might say. This is not meant as a comparison, but simply an assertion that there is value in both approaches and that I need not bend to pressures from one side or another in choosing my own direction. As Polonius counseled Hamlet: "To thine own self be true" (Ballora, 2021).

What fascinated me when I read this passage was that these conclusions in fact aligned closely with my own mentality, and they seemed to provide a basis for dealing with matters regarding artistic identity, expression and finding and preserving my own unique compositional voice in working with sonified material. I have to admit that it was quite liberating to realize that my deep psychological and philosophical battles with myself over the past 4 years, particularly regarding whether and to what extent I could meaningfully exert my own personal artistic influence and expression onto composing works using the sonification of data from a scientific domain, were also shared by with other practitioners.

Therefore to summarize, this portfolio of works can be primarily considered as my personal, artistic take on cancer from a biomolecular standpoint, featuring a mixed collection of custom-made, data-driven patches used as composition and performance interfaces, as well as fixed and live musical and audiovisual compositions that makes use of raw (sonic) material generated from the sonification of data pertaining to the same context. It is in essence a promotional, artistic portfolio for the science of cancer research, aiming to connect with the listeners' "hearts and minds", engaging with them from an alternate musical perspective and potentially educating them – albeit in an artistic, abstract, and sometimes even obscure way – on both the science behind cancer research and the human effort that goes into it. In addition, considering that the field of data sonification, and much less music composed within it, are still relatively newfound and unfamiliar to most audiences, a useful side effect of the listeners' encounter with such works is the fact that they learn about the field and process of data sonification itself. This is of course contingent upon such poietic information regarding the work being made available to them through programme notes, or similar means.

Of course, I concede that as an outreach effort, the efficacy of this portfolio and each work in connecting intellectually and emotionally with audiences should be objectively evaluated, and this research is unfortunately not included in this portfolio. The reason for this was primarily a lack of sufficient time, further exacerbated by the hindrance of the COVID-19 pandemic, which threw a veil of isolation around artists, separating them from their audiences to a great extent. It is also worth noting that as far as my outreach effort goes, I acknowledge that my take on the science behind cancer and my approaches in alluding to it in my compositions in this portfolio have been for the most part personal and subjective. Ultimately, how and to what extent listeners may engage with the resulting works remains beyond my intentions and final control.

As a composer who started out his PhD journey with practically no prior knowledge and experience in the field of data sonification and computer music, I believe above all that my project has been a lengthy and invaluable learning curve that has enabled me to not only gain valuable knowledge and practical experience in (music) programming, data sonification and algorithmic music composition and improvisation, but to also question and reflect on the approaches to, and implications of dealing with data sonification as an artist, which I believe is a significant insight to have gained. In addition to my contributions in the form of publications, my hope is that this body of works, and the details of my conceptual, technical and musical approaches in this project, could provide a useful roadmap for those composer-programmers who wish to undertake similar research.

**Future Research**

Having been actively engaged in the field of data sonification over the past 4 years, the prospect of future research and exploration of the science-art dialogue, especially when it comes to creating music and sound-art using data sonification is very intriguing to me at this point in my career as a composer and sound-artist. To me, the world of science is infinitely vast and the access to such fascinating contextual scientific resources, within various fields, opens up multiple pathways to explore, develop and promote both the scientific and artistic approaches to data sonification, creating interactive and educational tools, music, installations, etc. which could investigate the different facets of this dialogue, and in particular the

engagement and responses of audiences of various backgrounds to it. In that regard, I plan to undertake such collaborative science-art research projects in the medium of music, sound-art and audiovisual-art, hopefully through post-doctoral research or other funded opportunities, with a specific focus on wider audience engagement and the objective evaluation of the latter.

# BIBLIOGRAPHY


- Hanahan, D. and Weinberg, Robert A. (2011). Hallmarks of Cancer: The Next Generation. *Cell*, [online] 144(5), pp.646–674. Available at: https://www.cell.com/cell/fulltext/S0092-8674(11)00127-9.

- Walker, B.N. and Nees, M.A. (2011). Theory of Sonification. In: T. Hermann, A. Hunt and J.G. Neuhoff, eds., *The Sonification Handbook*. [online] Berlin, Germany: Logos Verlag, pp.9–39. Available at: https://sonification.de/handbook/download/TheSonificationHandbook-HermannHuntNeuhoff-2011.pdf.

- Kramer, G., Walker, B., Bonebright, T., Cook, P., Flowers, J., Miner, N. and Neuhoff, J. (2010). Sonification Report: Status of the Field and Research Agenda. *Faculty Publications, Department of Psychology*. [online] Available at: https://digitalcommons.unl.edu/psychfacpub/444.

- Brazil, E. and Fernström, M. (2011). Auditory Icons. In: T. Hermann, A. Hunt and J.G. Neuhoff, eds., *The Sonification Handbook*. [online] Berlin, Germany: Logos Verlag, pp.325–338. Available at: https://sonification.de/handbook/download/TheSonificationHandbook-HermannHuntNeuhoff-2011.pdf.

- Dombois, F. and Eckel, G. (2011). Audification. In: T. Hermann, A. Hunt and J.G. Neuhoff, eds., *The Sonification Handbook*. [online] Berlin, Germany: Logos Verlag, pp.301–324. Available at: https://sonification.de/handbook/download/TheSonificationHandbook-HermannHuntNeuhoff-2011.pdf.

- Grond, F. and Berger, J. (2011). Parameter Mapping Sonification. In: T. Hermann, A. Hunt and J.G. Neuhoff, eds., *The Sonification Handbook*. [online] Berlin, Germany: Logos Verlag, pp.363–397. Available at: https://sonification.de/handbook/download/TheSonificationHandbook-HermannHuntNeuhoff-2011.pdf.

- Asquith, L. (2013). *Listening to data from the Large Hadron Collider | Lily Asquith |TEDxZurich*. Available at: https://youtu.be/iQiPytKHEwY.

- Hermann, T. (2011). Model-Based Sonification. In: T. Hermann, A. Hunt and J.G. Neuhoff, eds., *The Sonification Handbook*. [online] Berlin Germany: Logos Verlag, pp.399–427. Available at: https://sonification.de/handbook/download/TheSonificationHandbook-HermannHuntNeuhoff-2011.pdf.

- Capanna, A. (2001). Iannis Xenakis:Architect of Light and Sound. *Nexus Network Journal*, [online] 3(1), pp.19–26. Available at: https://link.springer.com/article/10.1007%2Fs00004-000-0003-4.

- Dunn, J. and Clark, M.A. (1999). "Life Music": The Sonification of Proteins. *Leonardo*, [online] 32(1), pp.25–32. Available at: https://www.jstor.org/stable/1576622.

- Antarktika. (2006). *»ANTARKTIKA«A Climatic Time-travel - Concert for String Quartet, Live Electronics and Video by Frank Halbig with the Helios String Quartet*. [online] Available at: http://www.antarktika.at/ [Concept].

- Scaletti, C. (2013). *QUANTUM – Mu Psi || Carla Scaletti*. [online] Carlascaletti.com. Available at: https://carlascaletti.com/sounds/sound-art/quantum/.

- Wilson, S., Vasilakos, K., McCauley, T., Khosravi Mardakheh, M., Margetson, E. and Yeung, T.W. (2020). Sonification of High Energy Physics Data Using Live Coding and Web Based Interfaces. In: *Proceedings of the International Conference on New Interfaces for Musical Expression*. [online] The International Conference on New Interfaces for Musical Expression (NIME). Available at: https://www.nime.org/proceedings/2020/nime2020_paper76.pdf.

- Vickers, P. (2017). Sonification and Music, Music and Sonification. In: M. Cobussen, V. Meelberg and B. Truax, eds., *The Routledge Companion to Sounding Art*. London: Routledge, pp.135–144.

- Scaletti, C. (2018). Sonification ≠ Music. In: R.T. Dean and A. McLean, eds., *The Oxford Handbook of Algorithmic Music*. New York: Oxford University Press, pp.363–386.

- Christensen, E. (2003). Overt and Hidden Processes in 20th Century Music. In: J. Seibt, ed., *Process Theories*. [online] Dordrecht: Springer, pp.97–117. Available at: https://doi.org/10.1007/978-94-007-1044-3_5.

- Gresham-Lancaster, S. (2012). Relationships of sonification to music and sound art. *AI & Society*, [online] 27(2), pp.207–212. Available at: https://doi.org/10.1007/s00146-011-0337-3.

- Lucier, A. (1965). *Music for Solo Performer*. [Vinyl, LP] US: Lovely Music, Ltd. – VR 1014. Available at: https://youtu.be/bIPU2ynqy2Y.

- Straebel, V. and Thoben, W. (2014). Alvin Lucier's Music for Solo Performer: Experimental music beyond sonification. *Organised Sound*, [online] 19(1), pp.17–29. Available at: https://www.straebel.com/files/Straebel-Thoben%202014_Lucier%20M4SP.pdf.

- Supper, A. (2013). Sublime frequencies: The construction of sublime listening experiences in the sonification of scientific data. *Social Studies of Science*, [online] 44(1), pp.34–58. Available at: https://journals.sagepub.com/doi/pdf/10.1177/0306312713496875.

- Vaghi, K. (2015). *Company Gilles Jobin in "Quantum", Tanz in August, Berlin*. [online] *bachtrack*. Available at: https://bachtrack.com/review-gilles-jobin-quantum-tanz-in-august-berlin-august-2015.

- Ballora, M., Pennycook, B., Ivanov, P.C., Glass, L. and Goldberger, A.L. (2004). Heart Rate Sonification: A New Approach to Medical Diagnosis. *Leonardo*, [online] 37(1), pp.41–46. Available at: https://direct.mit.edu/leon/article/37/1/41/44575/Heart-Rate-Sonification-A-New-Approach-to-Medical.

- Ballora, M. (2010). Sonification Of Web Log Data. In: *International Computer Music Conference Proceedings*. International Computer Music Conference. pp.498–501.

- McCandless, D. (2014). *About — Information is Beautiful*. [online] Information is Beautiful. Available at: https://informationisbeautiful.net/about/.

- Ballora, M. (2016). Music of Migration and Phenology: Listening to Counterpoints of Musk Ox and Caribou Migrations, and Cycles of Plant Growth. In: *Proceedings of the 22nd International Conference on Auditory Display - ICAD 2016*.

- Ying, H. et al (2012). Oncogenic Kras Maintains Pancreatic Tumors through Regulation of Anabolic Glucose Metabolism. *Cell*, [online] Vol 149(3), pp. 656-679. Available at: http://www.cell.com/cell/fulltext/S0092-8674(12)00352-2.

- Genetics Home Reference. (2015). *KRAS gene*. [online] Available at: https://ghr.nlm.nih.gov/gene/KRAS#conditions.

- de Campo, A. (2007). Toward a Data Sonification Design Space Map. In: *Proceedings of the 13th International Conference on Auditory Display*. [online] International Conference on Auditory Display (ICAD). pp.342–347. Available at: http://hdl.handle.net/1853/50042.

- Alexjander, S. (1994). *Sequencia*. [CD, Album] Science & The Arts. Available at: https://open.spotify.com/album/2WFCW6wktz6vM1pdvW2uQ0?autoplay=true.

- Deamer, D. and McLaughlin, R. (1990). *DNA Music / DNA Suite*. [Album] Available at: https://www.discogs.com/Dr-David-Deamer-Riley-McLaughlin-DNA-Music-DNA-Suite/release/8612946.

- Schwarz, D., Beller, G., Verbrugghe, B., Britton, S. and Ircam – Centre Pompidou (2006). Real-Time Corpus-Based Concatenative Synthesis with CataRT. In: *Proceedings of the 9th International Conference on Digital Audio Effects (DAFx-06)*. [online] Available at: http://recherche.ircam.fr/equipes/analyse-synthese/schwarz/publications/dafx2006/catart-dafx2006-long.pdf.

- iCON Pro Audio. (n.d.). *Platform M*. [online] Available at: https://iconproaudio.com/product/platform-m/.

- Meireles, C. (2001). *Babel*. [Radios, Lighting and Sound].

- Barson, T. (2011). *Babel 2001*. [online] Tate. Available at: https://www.tate.org.uk/art/artworks/meireles-babel-t14041.

- Foster, B.R. (2018). *The Epic of Gilgamesh*. 2nd ed. New York ; London: W.W. Norton & Company.

- MaxScore 2. (n.d.). *MaxScore for Max and Ableton Live – Music Notation for Max and Ableton Live*. [online] Available at: http://www.computermusicnotation.com/#Projects.

- Stockhausen, K. (1995). *Kontakte : für elektronische Klänge, Klavier und Schlagzeug (Pianist, Schlagzeuger, Klangregisseur), 1958-60, Werk Nr. 12 1/2*. Stockhausen-Verlag.

- Mardakheh, M. (2021). Musical Model-based Sonification of Protein Fold-change Data in Cancer Cells: A 3D, multi-channel, Audiovisual Instrument for the Production of Musical Sonifications. In: *Proceedings of the International Computer Music Conference (ICMC 2021)*. [online] Available at: http://icmc2021.org/proceedings/ICMC2021_Paper-02-04.pdf.

- Hermann, T., and Ritter, H. (1999). Listen to your data: Model-Based Sonification for Data Analysis. In GE Lasker & MR Syed, eds. *Advances in intelligent computing and multimedia systems* . Windsor, Ontario: Int. Inst. For Advanced Studies in System research and cybernetics, pp. 189-194.

- Tunnermann, R. and Hermann, T., (2009). Multi-touch interactions for model-based sonification. In: *Proceedings of the 15th International Conference on Auditory Display*. Copenhagen, Denmark: International Community for Auditory Display. [online] Available at: http://www.icad.org/Proceedings/2009/TunnermannHermann2009.pdf.

- Bovermann, T., Hermann, T. and Ritter, H. (2006). Tangible Data Scanning Sonification Model. In: *Proceedings of the 12th International Conference on Auditory Display*. London, UK. [online] Available at: https://www.icad.org/Proceedings/2006/BovermannHermann2006.pdf.

- Hermann, T., Meinicke, P. and Ritter, H. (2000). Principal Curve Sonification. In: *Online Proceedings of the 6th International Conference on Auditory Display*. Atlanta, Georgia, USA: International Community for Auditory Display. [online] Available at: https://www.icad.org/Proceedings/2000/HermannMeinicke2000.pdf.

- K. Mardakheh, F., Z. Sailem, H., Kümper, S., J. Tape, C., R. McCully, R., Paul, A., Anjomani-Virmouni, S., Jørgensen, C., Poulogiannis, G., J. Marshall, C. and Bakal, C. (2017). Proteomics profiling of interactome dynamics by colocalisation analysis (COLA). *Mol. BioSyst.*, [online] 13(1), pp. 92-105. Available at: https://pubs.rsc.org/en/content/articlehtml/2017/mb/c6mb00701e.

- Beer, I., Barnea, E., Ziv, T. and Admon, A., 2004. Improving large-scale proteomics by clustering of mass spectrometry data. *Proteomics*, [online] 4(4), pp. 950-960. Available at: https://doi.org/10.1002/pmic.200300652.

- Hayflick, L. (2011). *Leonard Hayflick - Cell immortalization (139/187)*. [online] www.youtube.com. Available at: https://youtu.be/x4hMCDC54Sw.

- Max Online Documentation. (n.d.). *Working with OpenGL - Max 8 Documentation*. [online] Available at: https://docs.cycling74.com/max8/vignettes/working_with_opengl_topic.

- Ikeda, R. (2006). *Datamatics*. [Audiovisual Concerts, Installations, Publications and CD Releases] Available at: https://www.ryojiikeda.com/project/datamatics/.

- The American Cancer Society Medical and Editorial Content Team (2018). Understanding What Cancer Is: Ancient Times to Present. *American Cancer Society*. [online] Available at: https://www.cancer.org/cancer/cancer-basics/history-of-cancer/what-is-cancer.html.

- Avicenna (2014). *Avicenna Canon of Medicine Volume 4: Systemic Diseases, Orthopedics and Cosmetics*. Translated by H. Doostdar. Chicago, Il: Kazi Publications.

- Stammers, S. (n.d.). *Microscopic View of Blood Cells Moving through Blood Vessels*. [online] Getty Images. Available at: https://www.gettyimages.co.uk/detail/video/microscopic-view-of-blood-cells-moving-through-stock-video-footage/143801955.

- Make Noise (n.d.). *Make Noise Co. | Tape & Microsound Music Machine*. [online] Make Noise. Available at: https://www.makenoisemusic.com/synthesizers/tape-and-microsound-music-machine.

- Ircam (2018). *Spat*. [online] Ircam Forum. Available at: https://forum.ircam.fr/projects/detail/spat/.

- Music Tribe Global Brands Ltd. (n.d.). *Behringer | Product | FCB1010*. [online] www.behringer.com. Available at: https://www.behringer.com/product.html?modelCode=P0089.

- Ballora, M. (2021). Sonifying Data: For the Art, for the Science and for What Lies Between. *Leonardo*, [online] 54(2), pp.223–227. Available at: https://doi.org/10.1162/leon_a_01997.

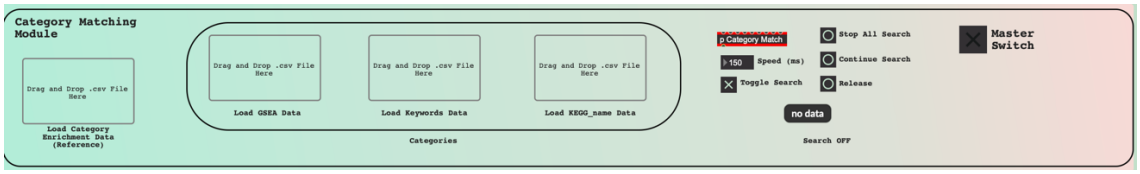
# APPENDIX A – FURTHER TECHNICAL DETAILS ON PATCHWORK

## A.1 Data Handler

Below are further details on the programming, and implementation of key modules and sub-patches of the *Data Handler* Max patch, elaborated in Chapter 5.

### Category Matching

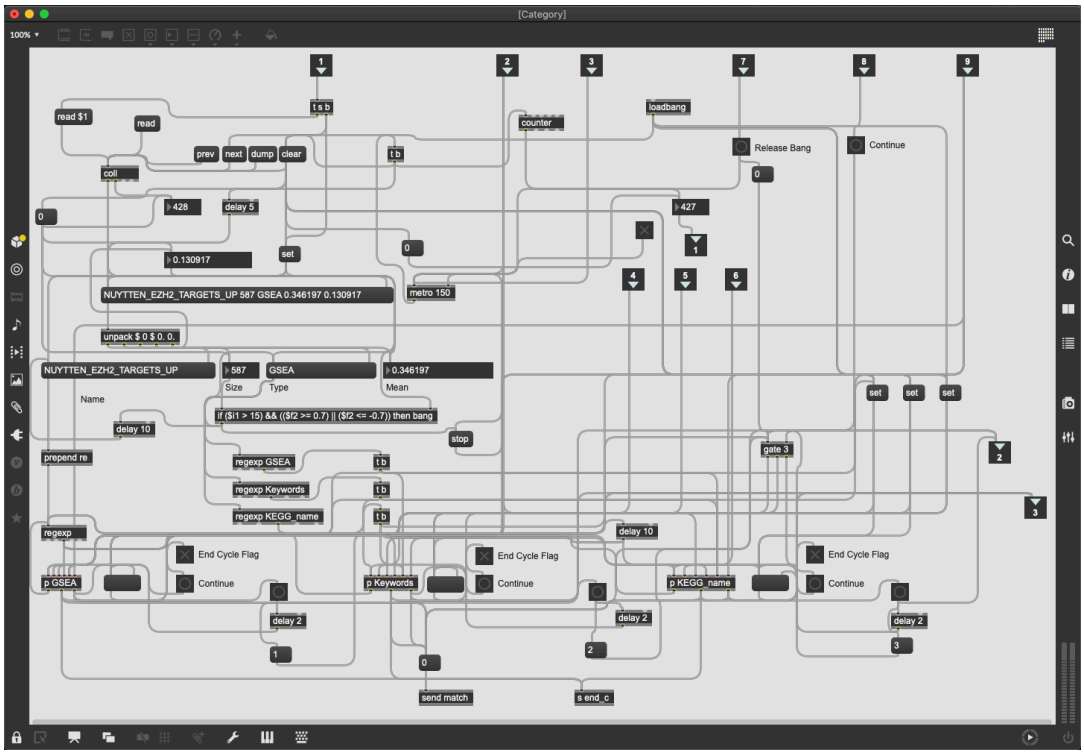
One important aspect of the data handling component is the C*ategory Matching* module. This section is effectively a search engine, involving a sub-patch which retains a time-based functionality similar to that of the traverse. However, its operation is independent and the dataset through which it navigates, is *Protein Category Enrichment.* This module is implemented within the GUI as seen in **Appendix Figure A. 1**.




Appendix Figure A. 1 – Data Handler Category Matching GUI

This distinct dataset, specifies the category of proteins/genes from the same KRAS on/off experiment, while also highlighting the significance of their activity levels based on the size of the measured samples. By using this dataset as a search key to find and cross reference the most significant proteins/genes in the initial, expanded dataset, *Data Handler* is able to pinpoint and 'lock' the sonic events, created by proteins/genes of notable importance, in a time-based manner. This 'locking' is done through sending a pause signal to all the *Data Traverse* sub-patches in all columns, and presenting only data values from that specific protein/gene, throughout the course of the entire experiment. The temporal characteristic of the function of the C*ategory Matching* module is essentially a musical and compositional design choice, creating two modes of operation; which from a sonification perspective, one is random (when the search has not been initiated or is in progress – and which I came to call as the

'Random Void' sound-world), and the other is the resulting sonification of one protein of significance in the experiment (when the search has concluded and the 'locking' has occurred). **Appendix Figure A. 2** below provides a closer look at the programming of this module.




Appendix Figure A. 2 – Data Handler Category Matching Patch

## A.2 AddSynth

This section provides further details on the programming, and implementation of key modules and sub-patches of the *AddSynth* Max Patch, elaborated in Chapter 5.

### Design

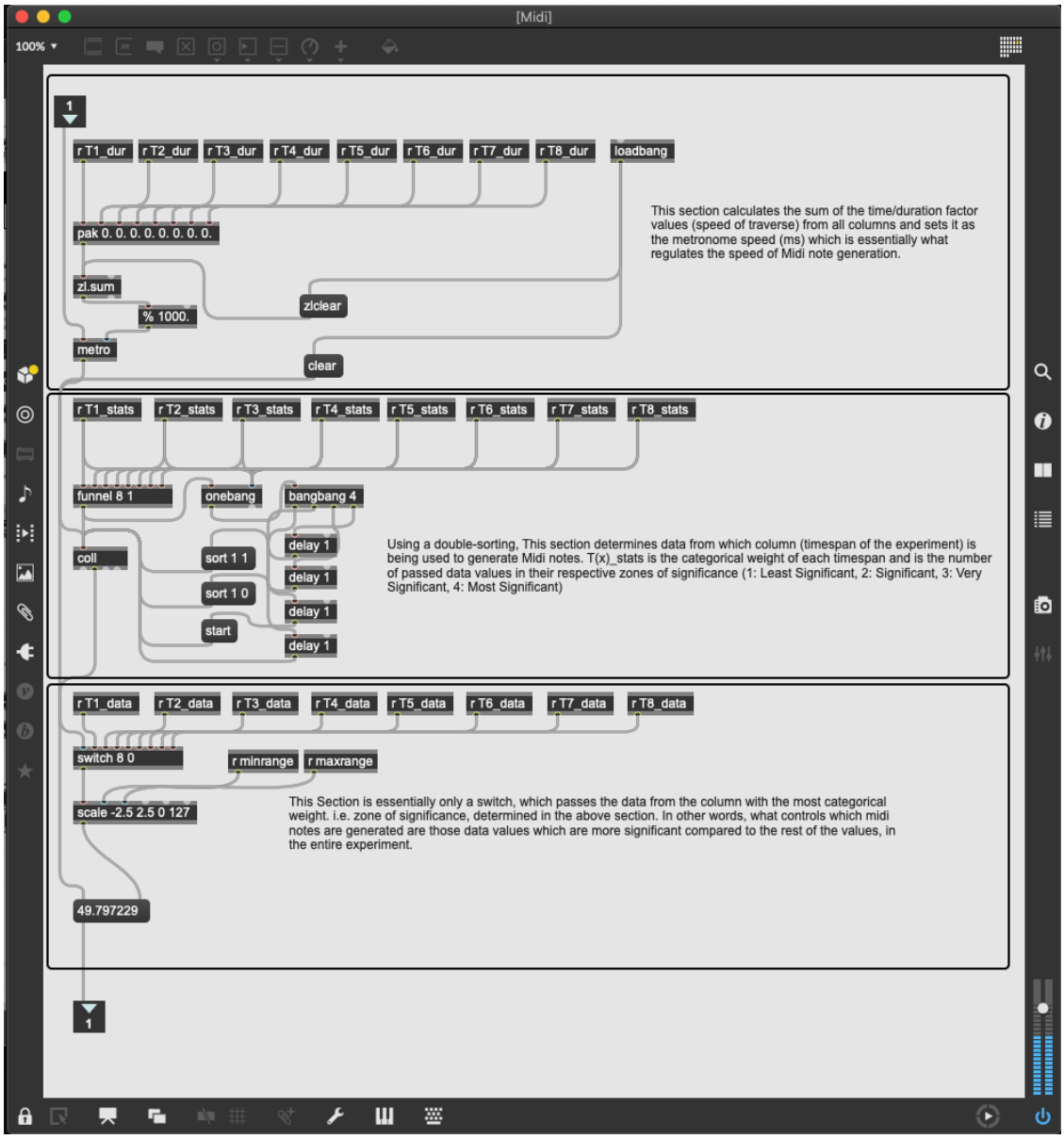
From a design perspective, *AddSynth* has three important functional modules that allow its operation. These are as follows:

- MIDI key/note generation
- Data processes/mappings

- Signal generation

**Midi key/note generation**

This section is responsible for receiving the data packages sent over from the *Data Handler*, and processing them algorithmically to produce MIDI notes, for each column/time-period of the data/experiment. The module's function can be divided into 3 steps outlined in **Appendix Figure A. 3** below.



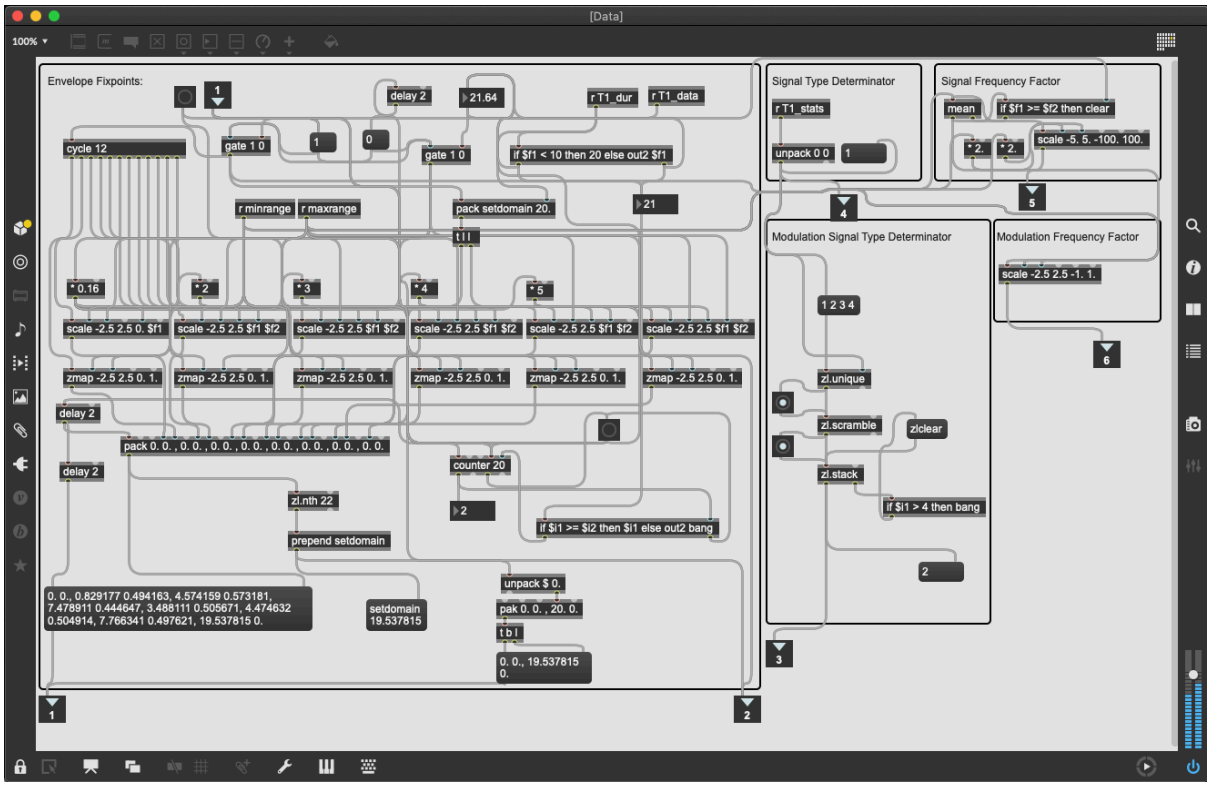

Appendix Figure A. 3 – AddSynth MIDI Key/Note Generation

**Data processes/mappings**

This section bears the task of generating ADSR envelope fix points on demand, from the data values and duration/time factor.

Timbre or Signal Type (waveform) is determined by the categorical weight. The more significant data values are recorded, the harsher the tone produced.

Signal Base Frequency / Modulation Frequency / Modulation Signal type are all linearly mapped to and determined by the data. **Appendix Figure A. 4** demonstrates the design of this sub patch.




Appendix Figure A. 4 – AddSynth Data Processes/Mappings

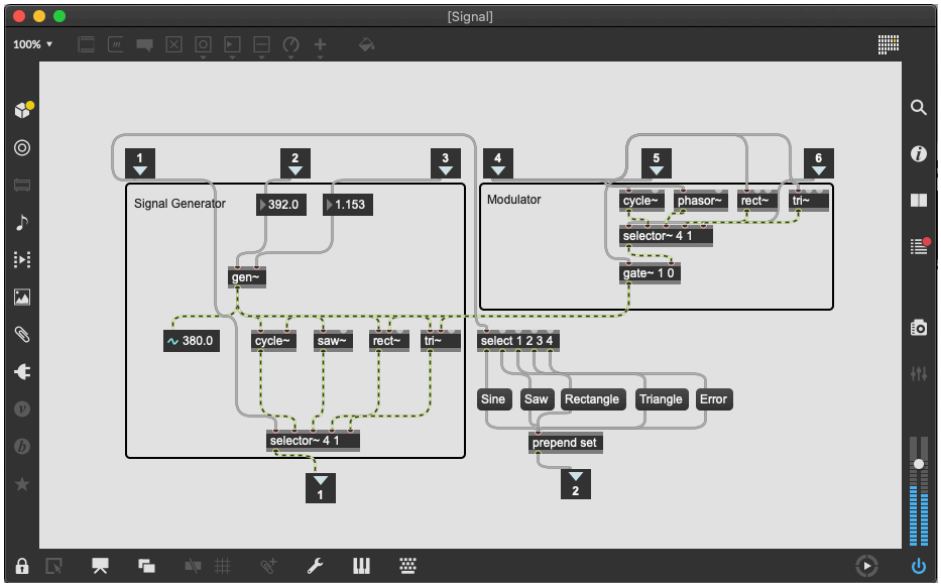
**Signal Generation**

This module consists of two main sections with the following functionalities:

1- Generation of the main signal, based on the ADSR envelope, MIDI note, Base Frequency factor and Signal type, which are all mapped to and determined by the data in the Data processes/mappings module elaborated above (see **Appendix Figure A. 4**).

2- Optional modulation of the main signal using a second signal whose type and frequency is mapped to and determined by the data, also using the above module.

**Appendix Figure A. 5** provides a snapshot of the signal generation module itself.




Appendix Figure A. 5 – AddSynth Signal Generation

## A.3 Modified, Data-driven cataRT (Concatenative Synthesizer)

This section provides further details on the programming, and implementation of the *Data dependencies* sub-patch of the *Modified Data-driven cataRT* Max Patch, elaborated in Chapter 5.

### Data dependencies

This sub-patch carries out the core data handling, processing and mapping. The data handling functionality implemented here varies significantly from the operation of the *Data Handler* patch and can be considered as an improvement. The main difference rests in preserving the vectorial quality (or temporal evolution) of the measured proteins/RNA fold-change in the used datasets. Since the resulting

datasets from various experiments (within the same context) might feature protein fold-change vectors of varying dimensions, the data handling functionality was developed exclusively to allow compatibility with such variations in dimensionality. In other words, the user can simply drag and drop protein fold-change vectorial data of any number of dimensions, in .csv format, and generate data-driven gestures.

To put it simply, the latter data-driven gestures are achieved by the mapping of each data vector (one protein's fold-change values measured over time) to a two-dimensional (x, y) vector (or trajectory) which is then applied to the x and y components of the cursor on cataRT.lcdm display. In other words, allowing the data vectors to 'play' the instrument at the highest, user interaction level. This is carried out in the following way:

1 – Protein fold-change data is loaded and stored.

2 – The minimum and maximum fold-change values in the entire dataset are extrapolated automatically and set as the minimum and maximum of the input mapping range for both the y component and the duration of the trajectories, with the possibility of manual scaling by the user via modifying the *Scaling Factor* parameter.

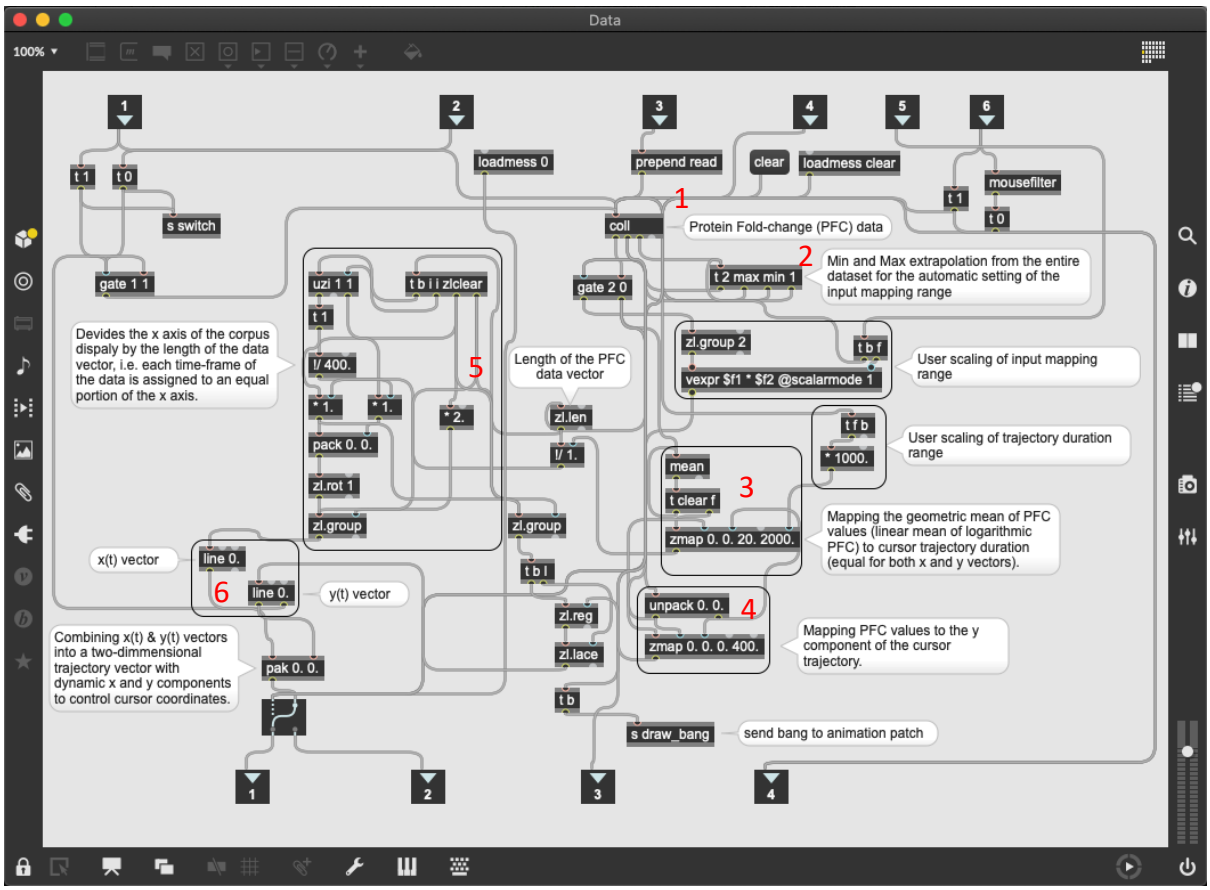
3 – The geometric mean of each protein's fold-change values is calculated and mapped to the overall duration of the cursor trajectory (for both x and y vectors), also with the possibility of manual scaling by the user via modifying the *Maximum Duration* parameter. This means that proteins with more significant levels of expression (higher geometric mean values) will produce lengthier trajectories.

4 – The data values are mapped to the y component of the trajectory vector, i.e. y(t).

5 – The length of the protein fold-change vector is calculated and used as the denominator of the length of the of the corpus display (x component). This means that each time dimension of each data vector will assume an equal part of the horizontal axis from left to right, which will then be traversed by the cursor at a specific pace/rate determined by the geometric mean of that data vector, i.e. x(t).

6 – The x(t) and y(t) trajectory vectors are combined and sent out to the corpus display to set cursor position.

**Appendix Figure A. 6** demonstrates the programming of this sub-patch with annotations below.

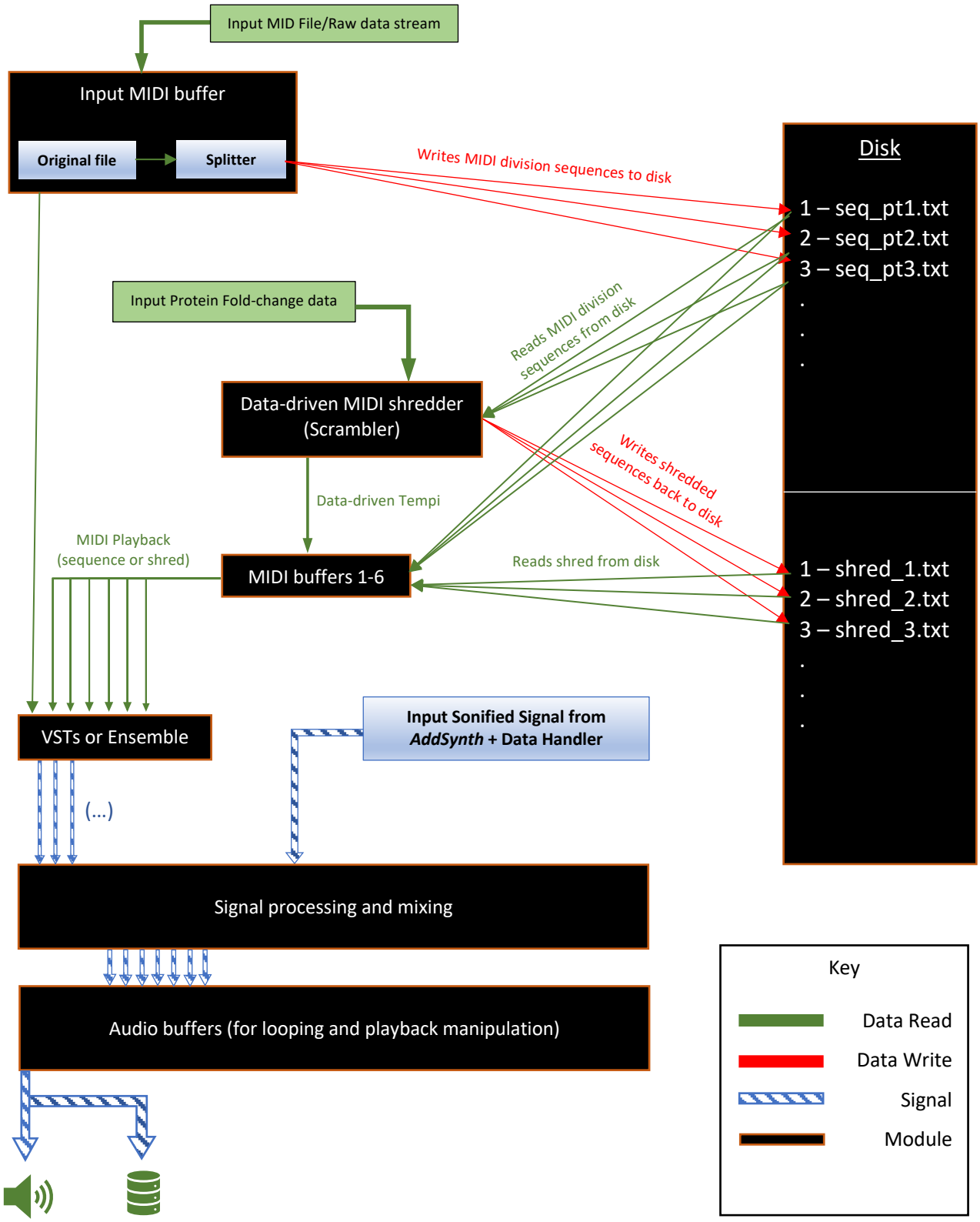



Appendix Figure A. 6 – Modified cataRT Data Dependencies Sub-patch

## A.4 Data-driven, MIDI VST Synth

This section provides further details on the programming, and implementation of key modules of the *Data-driven, MIDI VST Synth* Max patch, elaborated in Chapter 10. **Appendix Figure A. 7** provides a second look at the overall design of this patch.

**Design Overview**



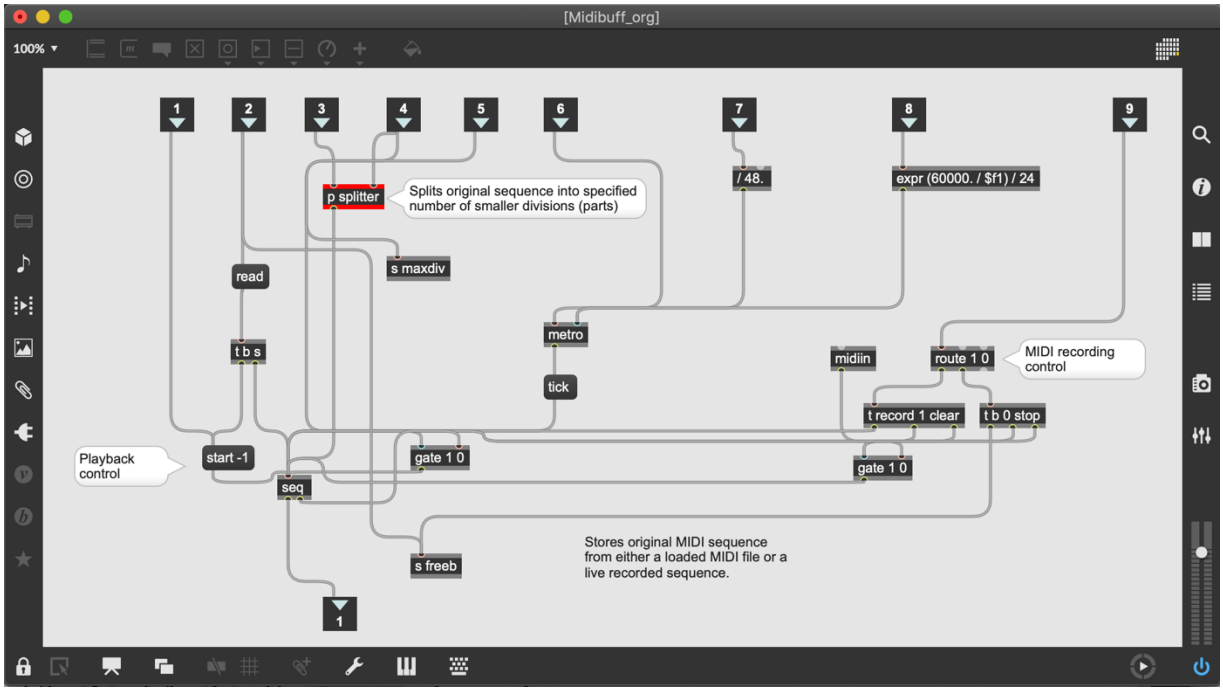

Appendix Figure A. 7 – Data-driven, MIDI VST Synth Design Diagram

**Input MIDI Buffer**

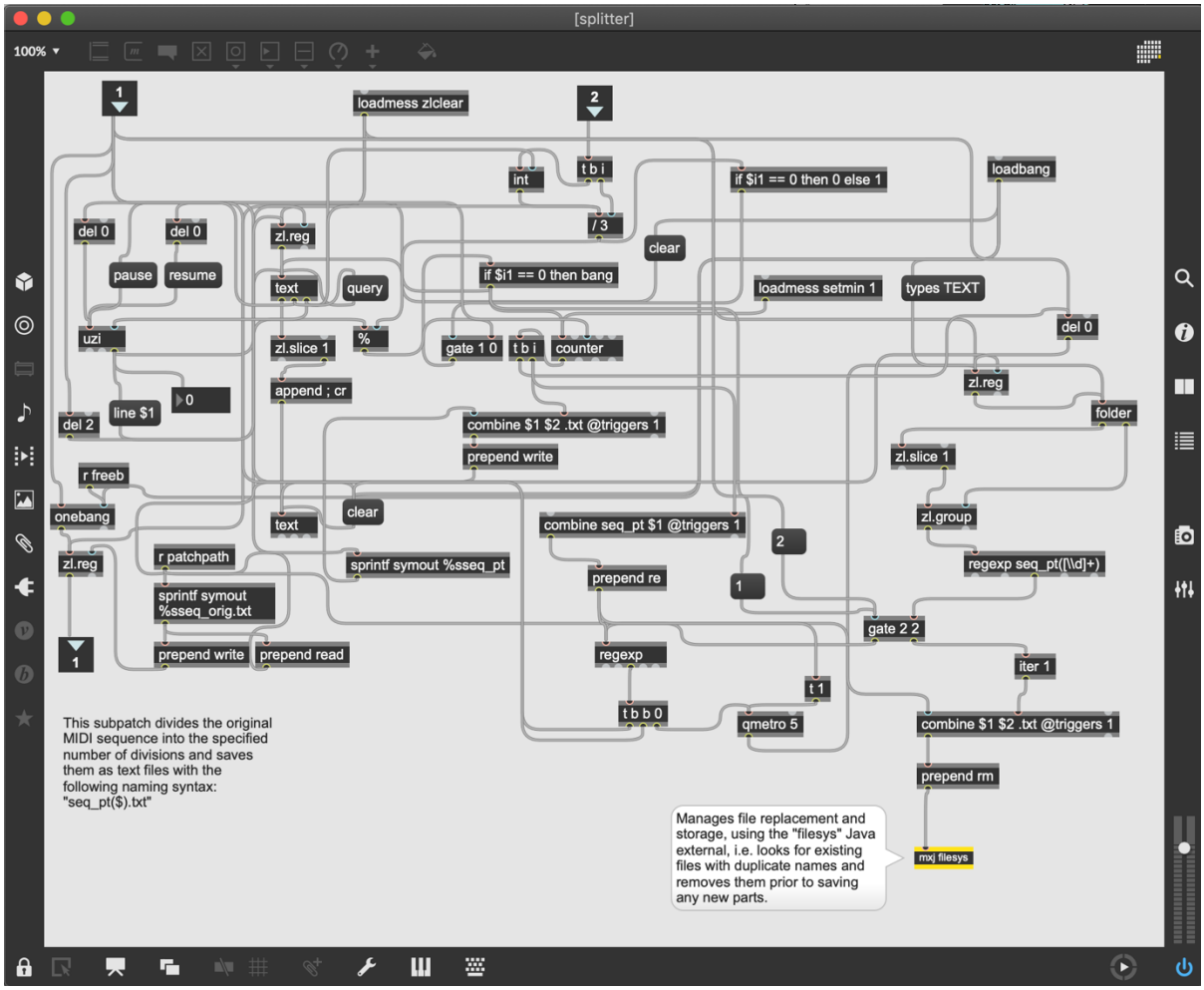
This module, demonstrated in **Appendix Figure A. 8**, has two key functions:

1 – Loading and storing of raw MIDI data, either from a file, or by live recording of MIDI data transmitted on any specified MIDI port. This can be useful towards improvisation and real-time changes to the input MIDI data.

2 – Splitting the stored MIDI data into a number of divisions specified by the user and saving these as .txt file on the disk for access by other modules. **Appendix Figure A. 9** shows the programming of the Splitter. The latter and other modules in this patch also make use of an external Java-based dependency, i.e. 'filesys', which among other functionalities, facilitates looking up any specific directory contents, filtering results based on filetype, and renaming/removing of specified files. This feature is used for the management of essential file storage and retrieval operations carried out by this patch, to ensure that there are no overwritten or duplicate files for each instance of MIDI division/shredding. In addition to storing and splitting the original input MIDI data, this module can also play/pause the latter.




Appendix Figure A. 8 – Data-driven MIDI VST Synth Input MIDI Buffer




Appendix Figure A. 9 - Data-driven MIDI VST Synth MIDI Splitter

**Data-driven MIDI Shredder (Scrambler)**

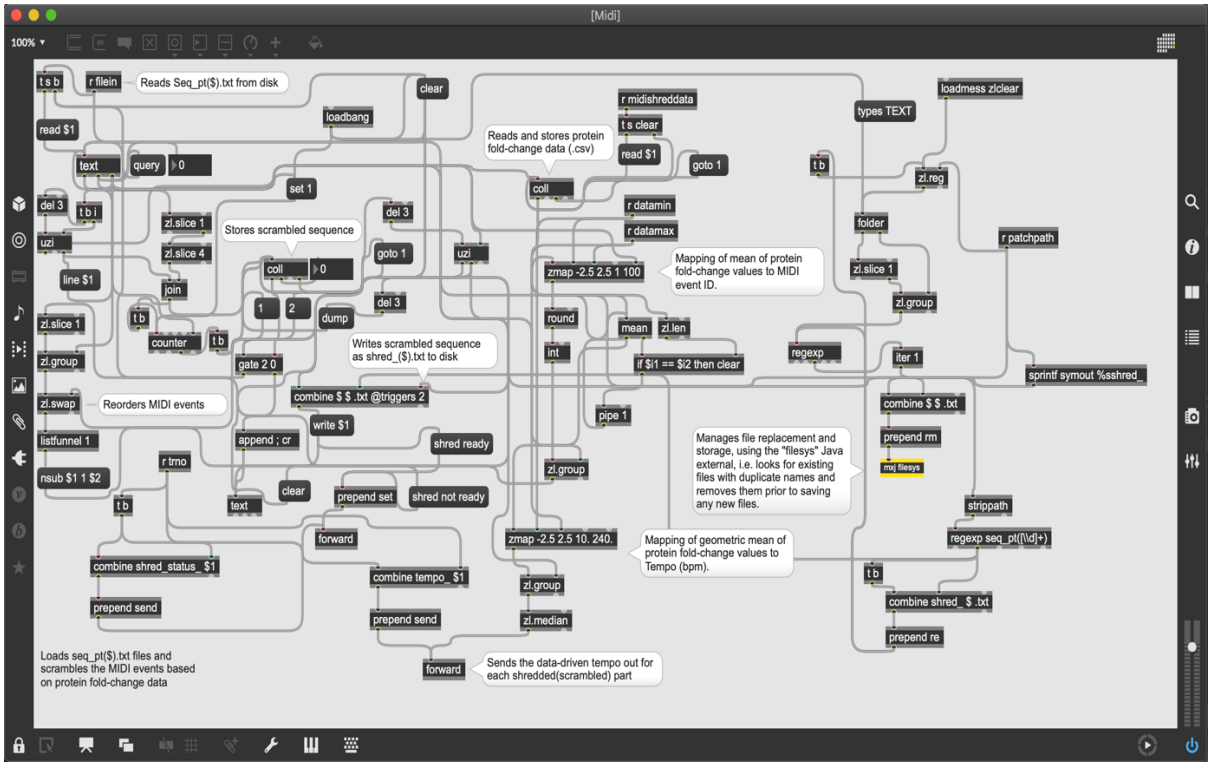
The Shredder module is essentially where the second-order sonification of data is carried out. Mappings between data values and synthesis parameters are implemented within two key functions of this module:

1 – Reordering (Scrambling) the MIDI events from the loaded part.

2 – Calculating a data-driven tempo for the loaded part based on the geometric mean of protein fold-change values.

For each loaded part (seq_pt($).txt), the vector values of each protein's fold-change measurement are scaled and mapped to the ID number of a MIDI event within the range of 1 to the total number of existing MIDI events in that part. The range of the input is set to [-2.5 , 2.5] by default, which is a suitable

range based on the characteristics of the used dataset. This range was acquired through trial and error. However to foster flexibility, the aforementioned range can also be modified at any time by the user via the range slider in the main GUI window, seen in Chapter 10, **Figure 10. 1**. The resulting reordered sequence is then saved onto the disk as files using the filename syntax of "shred_($).txt". The '($)' is a wildcard for the number of the respective part/shred. **Appendix Figure A. 10** exhibits the programming of the shredder.

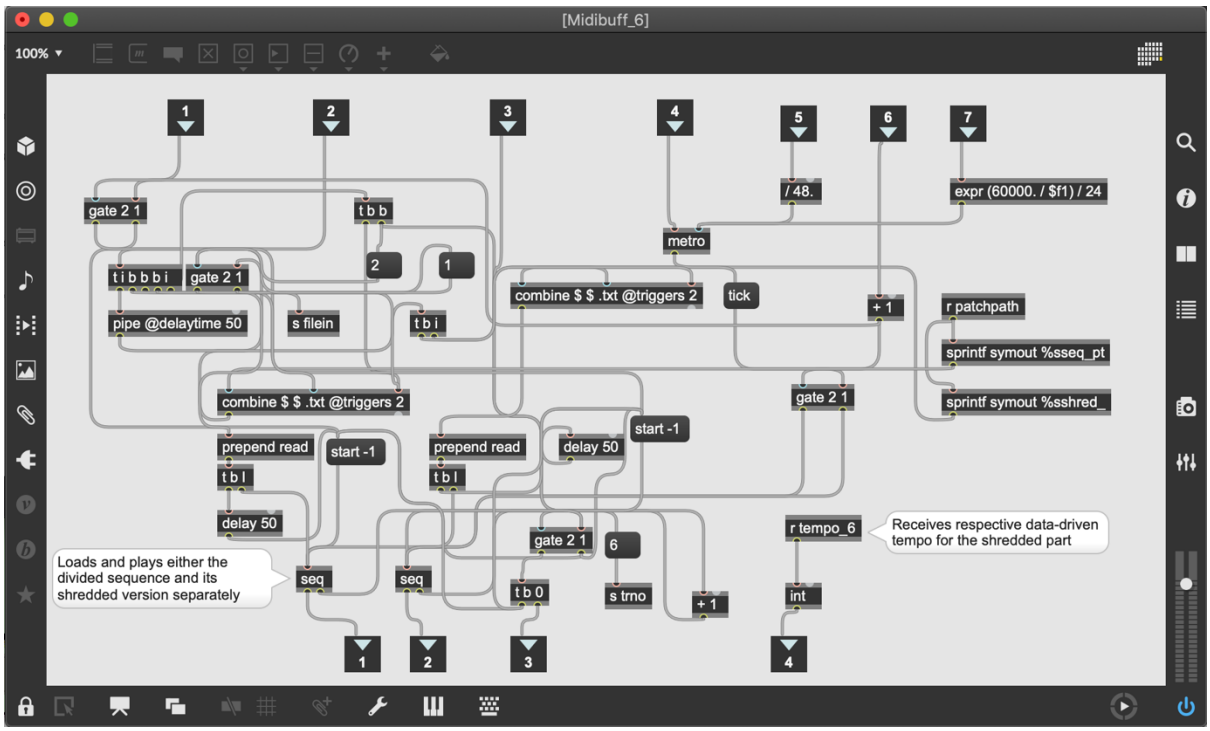



Appendix Figure A. 10 - Data-Driven MIDI VST Synth MIDI Shredder

### MIDI Buffers 1-6

As suggested by the name, these MIDI buffers bear the task of loading and playback of both the original sequence division, and its respective shredded version, separately. In other words, each MIDI Buffer, is essentially a double buffer, capable of storing and playing two separate MIDI sequences. In one instance of the MIDI Buffer, demonstrated below in **Appendix Figure A. 11**, the user has the ability to load any specific division and/or 'shred' of the original MIDI data. In the current version of this patch Buffers 1-5 are automatically loaded with sequences/shreds no. 1-5 respectively. The functionality of loading user specified sequences/shreds in buffer 6 can be easily applied to the other buffers with minor tweaking.

Apart from this difference, these buffers are all identical in design and copied across. The output MIDI stream from the playback of these buffers is  also sent back to the *AddSynth* patch to trigger sonified tones in addition to the latter's own data-driven ability to do this. This essentially creates a two-way handshaking between these two patches, which is also reinforced by additional implemented controllers in the GUI (see Chapter 10, **Figure 10. 1** – 'Toggle all modulation' and 'Regenerate all envelopes') to control *AddSynth*'s operation.




Appendix Figure A. 11 – Data-driven MIDI VST Synth MIDI Buffers 1-6

**VSTs/Ensemble**

This section of the patch bears the task of producing playback/performance of the instrumental parts. As mentioned earlier, this interface was designed with the possibility to accommodate handshaking with MaxScore, in order to produce real-time, aleatoric scores for instrumentalist during performance. In such a scenario, the output MIDI data stream (original part/shred) would be routed through MaxScore, instead of VSTs, and the resulting part provided to each instrumentalist. The captured audio signal from the live performance of the produced scores could then be routed back to the patch for processing and mixing in the appropriate module described in the next section. The aforementioned setup would of course

require further considerations and definite guidelines for realization as part of closer examination, which remains a future development goal for this system.

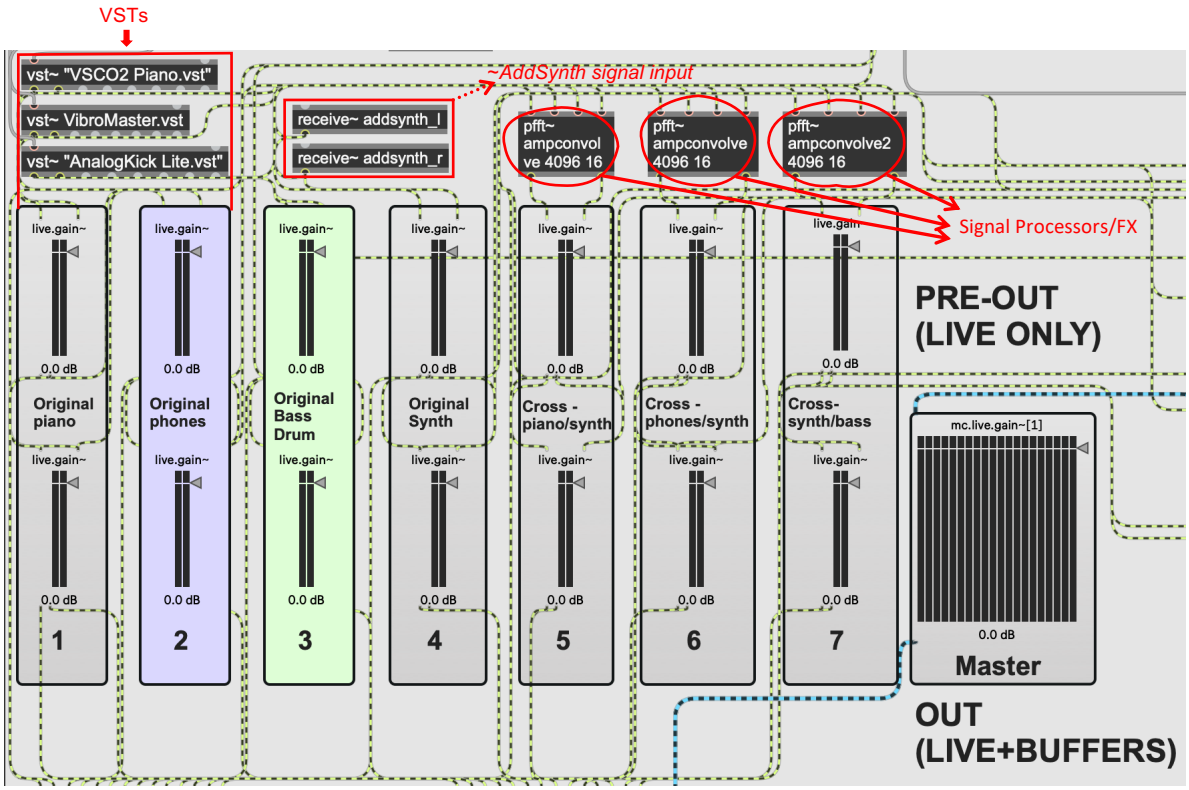
For the time being, the output MIDI data is routed and realized using VSTs. The versatility of using virtual instruments allows for a vast choice of instrumentation/ensembles. While the composition of the piece *Evading (Growth Suppressors)*, which solely utilizes this patch for its generation of raw sound material, uses a mixed ensemble of Piano, Bass Drum and Vibraphone, with little modification any ensemble arrangement up to 6 instruments can be explored using this patch.

**Signal Processing and Mixing**

In this module, audio signals from the VSTs/ensemble as well as the *AddSynth* patch, are routed through three separate layers of amplitude convolution/cross-synthesis effects. The raw, unprocessed signals are also routed through to output for maintaining *Dry/Wet* balance. It is worth noting that the arrangement of routing can of course vary based on the user's preference with minor required modification. The same also applies to using any other spectral processing effects. Since the broad objective behind this patch as a mixed-media instrument is to procure a sound-world comprising a mixture of electronic and instrumental sounds, the routing used in this instance of the patch was chosen as a result of trial and error with the aim of reaching textures in data-driven instrumental sounds that are affected, or metaphorically speaking corrupted/diseased by the more abrasive synthesized tones produced by *AddSynth*. This is an aesthetic consideration which alludes to the context of cancer.

Therefore, in addition to having the dry instrumental signals on tracks 1-3 and the dry *AddSynth* signal (synthesized tones) on track 4; the cross-synthesized outputs of each instrumental track with the *AddSynth* signal are included on tracks 5-7. **Appendix Figure A. 12** provides an overview of this module. The convolution/cross-synthesis effects used here were accessed from Max/MSP's generic spectral processing example patches, and modified minorly.

In addition to signal processing, this section also bears the functionality of a mixing desk in the GUI, providing two sets of faders: pre-out (for the live signals) and out-out (for a combination of signals from both live sources AND the audio buffers).




Appendix Figure A. 12 – Data-driven MIDI VST Synth Signal Processing and Mixing

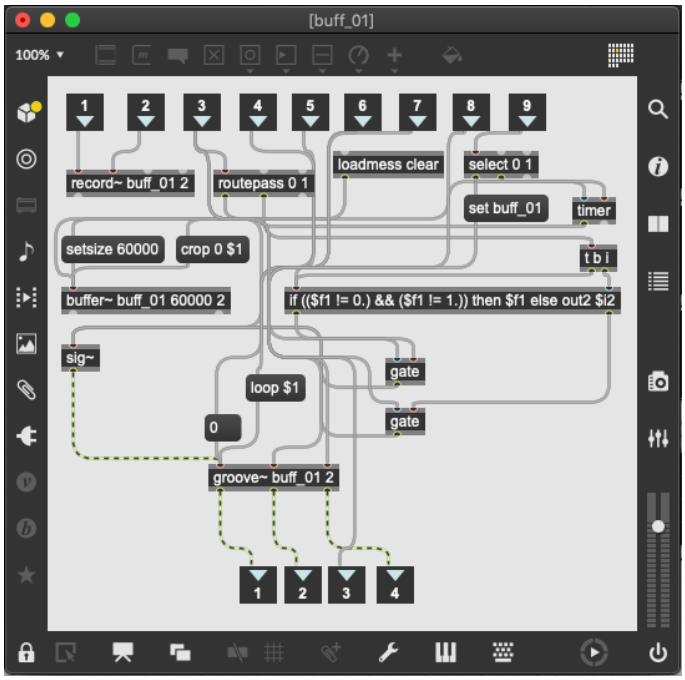
**Audio Buffers and Output Signal**

As pointed above, the 'out' multichannel signal (14ch) comprises a combination of the live signals + the audio buffers. The user/player has the ability to balance the levels of these signals using the provided faders.

There are 7 audio buffers provided in this interface, which are duplicates of the same module. The typical audio buffer, with its GUI as seen in **Appendix Figure A. 13**, provides basic functionalities such as playing/pausing, recording, looping, highlighting/selecting audio and modifying playback speed.


Appendix Figure A. 13 – Data-driven MIDI VST Synth Audio Buffer GUI

**Appendix Figure A. 14** provides a closer, under-the-hood look at the programming of the buffer component.




Appendix Figure A. 14 – Data-driven MIDI VST Synth Audio Buffer Programming

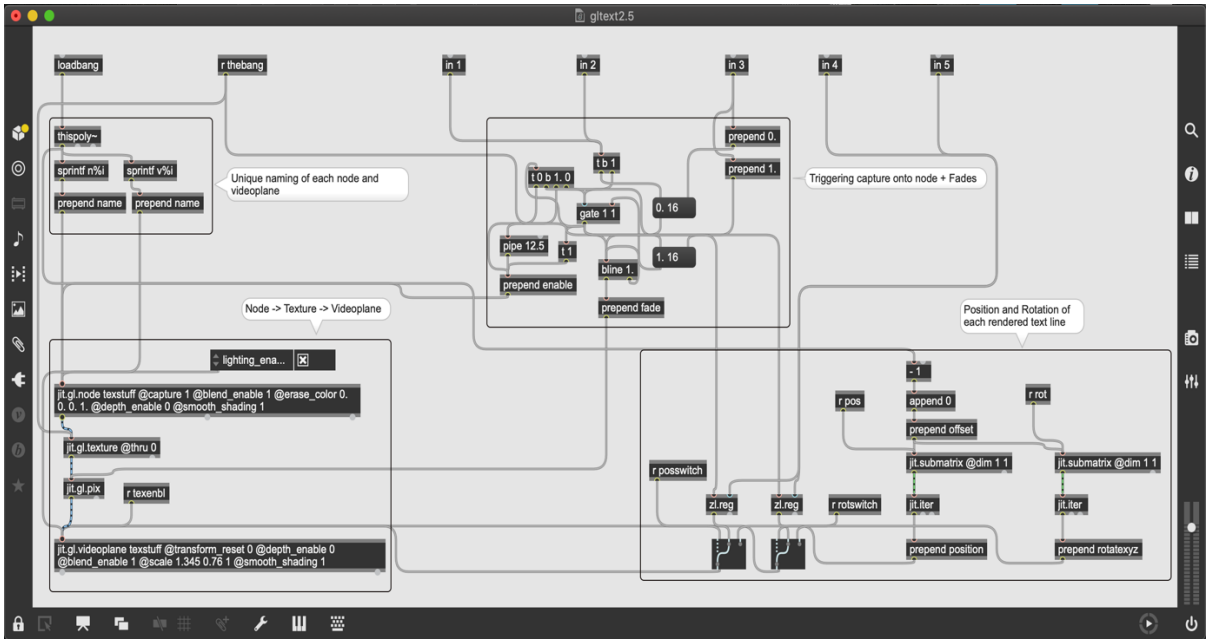
## A.5 Data-driven/Audio-reactive Animation Patch for Malignant Angiogenesis

This section provides further technical details on the programming, and implementation of the key modules and sub-patches of the *Data-driven/Audio-reactive Animation Patch for Malignant Angiogenesis*, elaborated in Chapter 14.

### Text Rendering Using Poly~

The main element in the live animations created by this patch is multiple rows/lines from the input protein fold-change dataset, rendered simultaneously as floating text in the 3D space, fading out and in

when a new row is introduced and replaces an existing one. This is implemented using the mc.poly~ object which is normally used for DSP procedures, but can also be modified and used for any other purpose. Interestingly, the latter task proved to be more challenging than initially expected, as Max's *jit.gl.text* object is unfortunately not at all CPU/GPU efficient, and having many instances of it loaded by the poly~ object resulted in a substantial drop in frame-rate. To tackle this problem, I devised a turnaround in which there is only need for one actively rendering jit.gl.text object, and the poly~ instead hosts multiple parallel gl.nodes, each with its subsequent jit.gl.texture, which can capture and store any rendered animation drawn to it. Using unique names for each node, texture and video plane (simply a 2D plane in 3D space), alongside a carefully-timed capture procedure, each row/line of the input data text rendered by the jit.gl.text is captured into its respective node/texture and projected passively onto its respective video plane. This means that the amount of time during which the jit.gl.text object is actively using processing resources for rendering a line of text is reduced down to milliseconds, which ultimately solves the frame-rate-drop problem. **Appendix Figure A. 15** demonstrates the poly~ object.

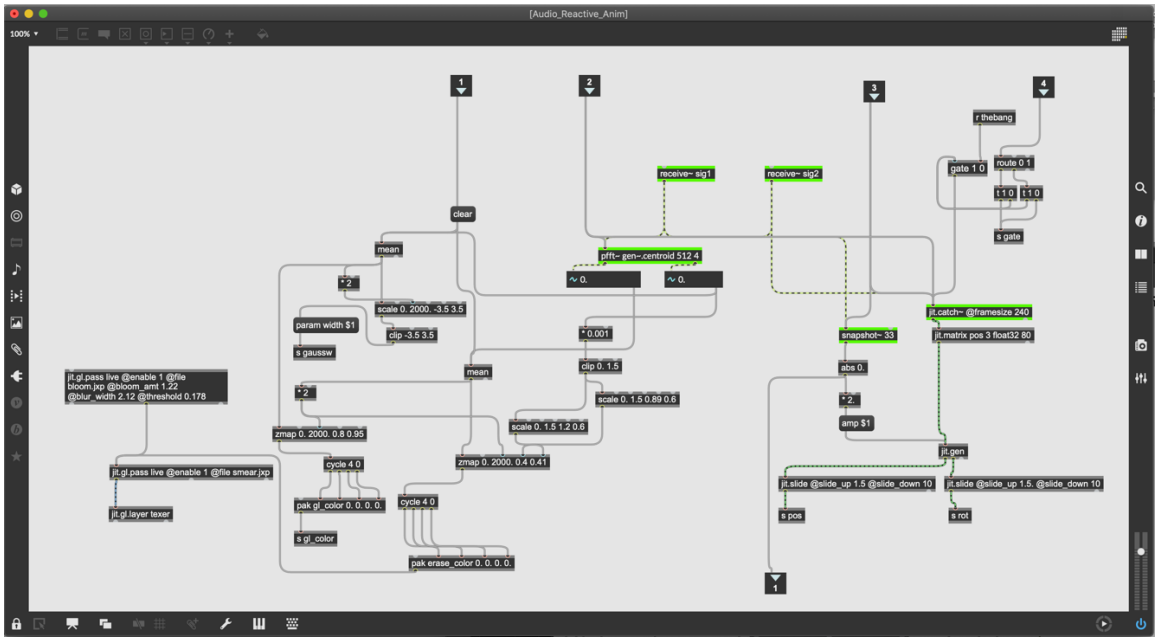



Appendix Figure A. 15 – Data-driven/Audio-reactive Animation Patch Text Rendering Using Poly~

**Audio-reactive Functionality**

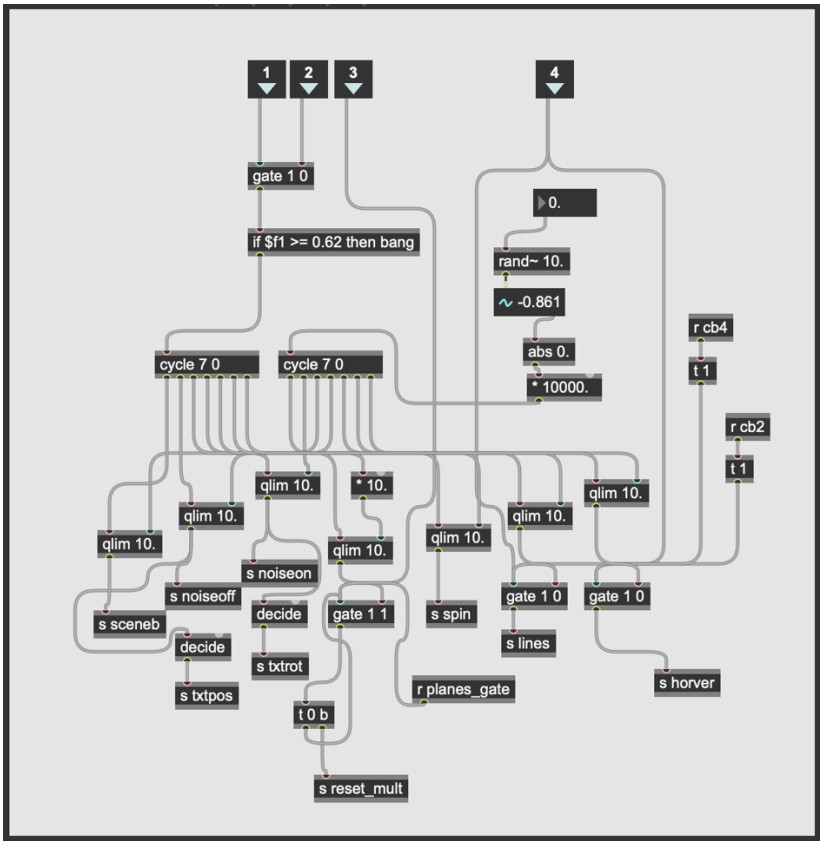
The audio-reactive functionality of this patch can be divided into two sections: 1- Animation and 2- Editing, which are described in turn below.

The audio-reactive animation is achieved using amplitude sampling of the passing audio signal, and mapping the resulting amplitude values to the position and rotation factor of the rendered text lines. Moreover, the spectral centroid value (brightness) of the passing signal is also mapped to other parameters i.e. color of text lines and other animated objects, erase color of the smear effect and width of the gaussian blur effect. **Appendix Figure A. 16** below shows a snippet of this section with the audio signal related objects highlighted in green.




Appendix Figure A. 16 – Data-driven/Audio-reactive Animation Patch Audio-reactive Functionality

The audio-reactive editing is attained using the same amplitude sampling of the audio signal as above, with the main difference of being gated at a specified threshold, i.e. any amplitude peak over 0.6 results in triggering an editorial action. In addition, a random signal generator is also used in conjunction with the latter amplitude sampling, resulting in a combination set of audio-reactive/stochastic editorial behavior. Using the round-robin algorithm, these triggers are mapped to various control parameters, e.g. changing the scene between the live visuals and pre-rendered animations, moving the camera, etc. **Appendix Figure A. 17** displays the programming of this section.




Appendix Figure A. 17 – Data-driven/Audio-reactive Animation Patch Audio-reactive Editing

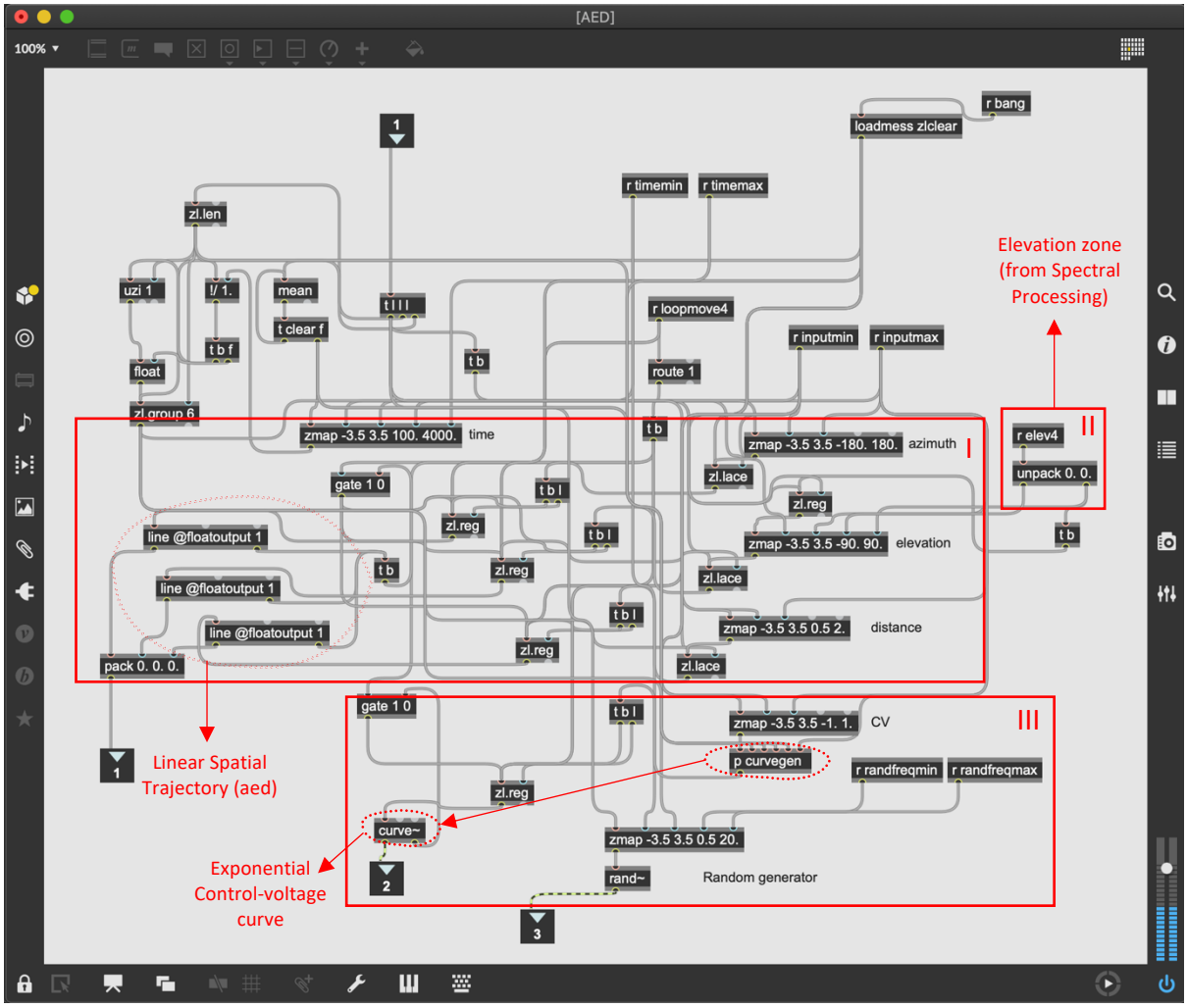
## A.6 Data-driven Ambisonic Spatializer and Make Noise Modular-Synth Modulator

This section provides further technical details on the programming, and implementation of the key modules and sub-patches of the *Data-driven Ambisonic Spatializer and Make Noise Modular Synth Modulator*, elaborated in Chapter 15.

### Data Handling and Mapping

The handling and mapping of protein fold-change data is carried out in the same vectorial manner as in the *Modified Data-driven cataRT* patch; i.e. the patch is compatible with datasets featuring data vectors of any number of dimensions, preserves information regarding the temporal evolution of data values, and carries out the mapping of data vectors to linear spatial trajectories, as well as exponential control-voltage curves. The latter functions are implemented within the *AED ramps* sub-patches, highlighted with the color yellow in **Figure 15. 1**, in Chapter 15. There are four identical instances of this sub-patch, each of which bears the task of outputting data-driven spatial trajectories and control voltages for one protein.

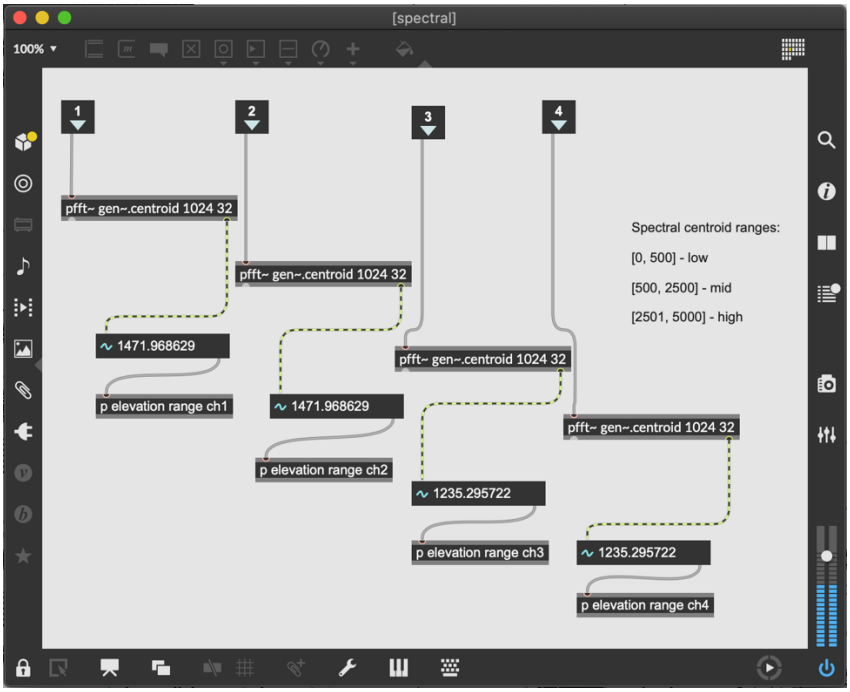
Therefore, the user is limited to inputting and mapping data vectors of four proteins from the source dataset at each turn. Moreover the user is also able to turn on/off looping for any/all trajectories (see **Figure 15. 1**). A closer look at the design of a typical *AED ramps* sub-patch is provided in **Appendix Figure A. 18** below.



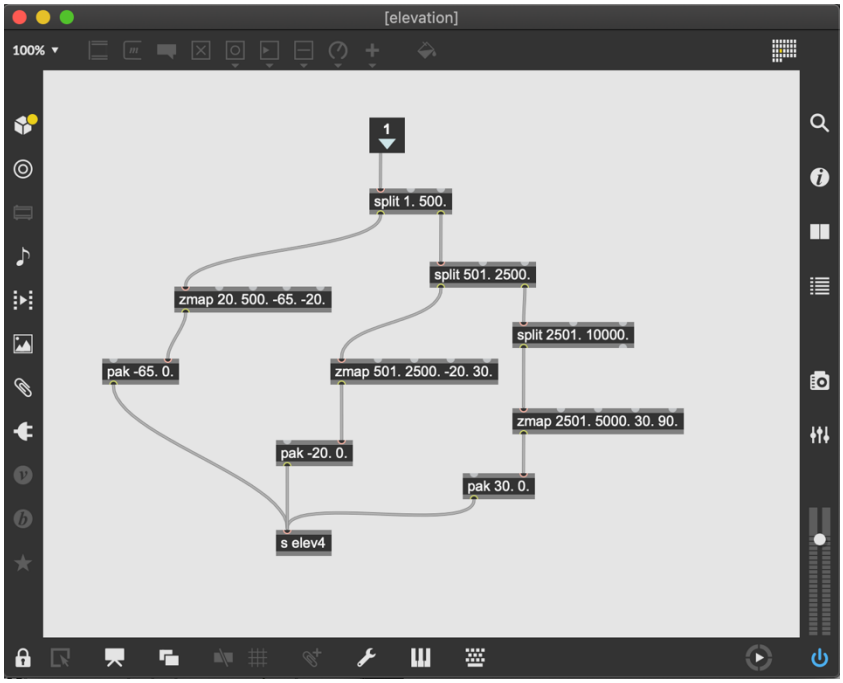

Appendix Figure A. 18 – Data-driven Ambisonic Spatializer & Make Noise Modulator AED Ramps Sub-patch

The name of this sub-patch references the use of the Spherical Coordinate System in the mapping of data vectors to spatial trajectories (Azimuth angle, Elevation angle & radial Distance). This coordinate system is compatible with the Spat library. As it can be seen in **Appendix Figure A. 18** , section I demonstrates the mapping of each incoming data vector to azimuth, elevation and distance parameters. Similar to the *Modified Data-driven cataRT*, the duration of each spatial trajectory is mapped to the mean value of its respective protein's data vector. The resulting three-dimensional, position vector is sent out to

Spat5.spat~ object for the real-time spatialization of the input audio signal designated to this specific protein. Section II receives feedback data from the *Spectral Processing* sub-patch (highlighted in blue in **Figure 29**), which pertains to the elevation zone of the spatial trajectory. Elevation zone here refers to a specified range for the elevation angle, e.g. [30 , 90] degrees.  This feature was implemented in order to achieve intuitive spatialization of sound via the real-time modification of the range of the elevation mapping based on the spectral centroid value of the output signal for each protein, i.e. brighter and high-frequency sounds will be spatialized in higher zones of elevation, while darker and lower frequencies will move closer to floor level. **Appendix Figures A. 19** & **A. 20** demonstrate the programming of the *Spectral Processing* sub-patch and the 'zoning' of the elevation parameter.




Appendix Figure A. 19 – Data-driven Ambisonic Spatializer & Make Noise Modulator Spectral Processing




Appendix Figure A. 20 – Data-driven Ambisonic Spatializer & Make Noise Modulator Elevation Zones

Section III (in **Appendix Figure A. 18**) exhibits the mapping of data vectors to exponential curves, in order to be sent out as control voltages to the modular synthesizer. Similar to the spatial trajectories, the duration of each exponential curve is determined by the mean of its respective protein's data vector values. Moreover, a random signal generator is included as an aesthetic choice for the purpose of attaining a higher level of sonic complexity, whose frequency is also mapped to the latter mean value. The output of the random signal generator is sent out as an additional, separate control voltage.

# APPENDIX B – MUSICAL MODEL-BASED SONIFICATION OF PROTEIN FOLD-CHANGE DATA IN CANCER CELLS

A 3D, multi-channel, Audiovisual Instrument for the Production of Musical Sonifications

This section features the full text of the article conceived and authored by myself (Milad K. Mardakheh), which is summarized and referenced in Chapter 11. This paper was presented and published in the 2021 International Computer Music Conference (ICMC) in Santiago, Chile. Formatting and Captions have been modified for its inclusion in this written commentary.


## Abstract

This application is designed specifically with the intention of yielding musical sonifications of the high-throughput measurements of protein fold-change within cancer cells, through the explicit use of the Model-based Sonification (MBS) technique. The mentioned measurements are acquired via the Mass-Spectrometry Proteomics Analysis experiments conducted on cancer cells by scientists at the laboratories of Barts Cancer Institute in London, UK; with whom the author has been collaborating over the course of his PhD project in Music Composition. The main reason for adopting MBS as the primary technique of sonification, in addition to strictly relying on Parameter-mapping, as with the various other patches created by the author during his research, is exploratory and essentially experimental in terms of exhausting the available approaches towards data sonification. The resulting application can be categorized as a generative musical instrument in the medium of electroacoustic music, the design of which can be regarded as a general framework for the model-based sonification of high-throughput and high-dimensional data, for artistic/musical purposes.


## 1. Introduction

This application attempts to bring together the two worlds of huge, numerical, protein fold-change data (with its inherent complexities and patterns), and electroacoustic music, with the purpose of creating an immersive and interactive audiovisual experience for the user/player. While its design primarily focuses

on prioritising musicality to the scientific analysis of the data in terms of the produced sonified material, significant attention has also been given to bring forth certain salient aspects of the source dataset, with the goal of preserving correspondence and relevance to the semantics of the source dataset. This is done so in order to achieve a balance between musical aesthetics and purely scientific sonification. Nevertheless, regardless of the ultimate efficacy of this musical sonification system in realizing the latter goal, as mentioned, the implemented complexities in its design largely favour musical aesthetics, and are as a result of a musical/compositional perspective. Therefore it will be difficult, if not impossible, to rigorously and accurately extrapolate specific information regarding the underlying data at all times. In other words, as a piece of software designed by a composer/programmer, this application is by no means intended to be used as a data analysis tool, but instead as a generative and exploratory tool in the medium of interactive Audiovisual art – with a specific focus on the 'audio' part. The target audience/user for this can be musicians/composers looking to generate data-driven sonorities accompanied by visuals (perhaps for live performances), or the general public, if deployed as an Audiovisual installation.

## 2. Model-Based Sonification

This technique of sonification can be summarized as creating a dynamic virtual model based on the characteristics of the data domain and allowing the user to interact with (excite) it, which in turn produces sonifications resulting from the data-driven acoustic properties of the model, in accordance to a specific *sonification model* chosen beforehand in the design process. In other words, *Model-based sonification mediates between the data and sound by means of a dynamic model* [1]. MBS analogously functions much like a musical instrument modelled on, or inspired by the data which demands interaction from the user in order to produce sounds that will inevitably have the characteristics of the underlying data space, on a more holistic basis and as a gestalt. This instrument-like characteristic adds an explorative and educational dimension to the system, in which the user can heuristically acquire the skills to operate the system, or play the instrument, as well as learning and comparing the produced sonifications of the underlying data. This is elaborated further down in this paper.

In contrast to parameter-mapping sonification which is the most commonly used technique in producing direct sonification from data, whereby each data variable is directly mapped to a corresponding sonic variable - which Gresham-Lancaster refers to as first-order sonification - [2], MBS instead deals with - second-order - sonification through a significant level of abstraction, in which a limited number of variables from the data domain are transposed into the model domain (*model architecture*) [1]. While this abstraction might in some cases come with the cost of losing minute details within the underlying data as represented in the sonic domain, it nonetheless facilitates the production of rich and complex sounds in a multimodal medium, as well as allowing an effective emphasis on salient aspects of the underlying dataset that are of importance to the user based on their objective. As a result, MBS bears the potential of conveying the sought information to the user much more efficiently and aesthetically, compared to first-order sonifications.

Furthermore, playability/interactivity is an intrinsic element within MBS which can open up an avenue towards musical/gestural expression in the closed loop of data, model, human interaction and sound [3]. This is an element which is lost to a significant degree in parameter-mapping sonification.

Most existing interactive model-based sonification systems serve as analysis or practical tools. For instance, in their work *AcouMotion*, Hermann, T. et al. have designed a combination hardware and software system which facilitates motor control by using model-based sonification as the main feedback channel, which in return allows for applications such as sports games for the visually impaired [4]. Another example is the work of P-J. Maes et al., *A Model-based Sonification System for Directional Movement Behavior*; in which, a virtual model of a person's *kinesphere* is developed which produces sonifications by the movement of the upper limbs of the user [5].

Some sonification systems also have a focus on certain musical and compositional elements in their designs, whilst still maintaining the primary goal of communicating information from the underlying data clearly and rigorously. For instance, the work of Diniz, N. et al. which had a significant impact on the design of this sonification system, outlines the use of electroacoustic composition techniques and the spectromorphological properties of sound [6] in their sonification model, in addition to an interface

design based on music cognition which allows for the exploration of the musical sonification output of the system [7]. Similarly, the Interactive Physics Sonification System (IPSOS), created by Wilson, S. et al., as an offspring of their Dark Matter project, utilises a web-based interactive interface with a similar focus on electroacoustic composition principles, to produce musical sonifications of sub-atomic particle collision data, derived from experiments conducted on the CMS detector at CERN Institute [8].

## 3. Design

A principal design directive of this application can be indicated as the creation of a real-time, multimodal and immersive environment for the user/player to interact with the sonification process, with the help of simultaneous visual and auditory cues. In other words, a coupling of data-visualisation and data-sonification; which the frameworks for MBS elaborated briefly below, demand in their design process.

### 3.1 Implementation

This application is solely implemented within the Max/MSP programming environment [9]. The visual and object-oriented programming of Max/MSP allows for the real-time feedback of audio and video in the design process, which makes it a suitable API for the implementation of the intuitive and experimental design of this application. Moreover, Max features both multichannel modular audio programming tools, as well as OpenGL animation design tools (through *Jitter*), which are beneficial in creating synchronized, real-time, multichannel audiovisual interfaces.

Nevertheless, using Max/MSP reduces portability and compatibility with different machines, as there is need for prior installation of the API to run its applications. There is of course the feature that allows for exporting standalone applications written in Max for both mac and windows operating systems, but this would eliminate the ability to make any possible modifications. For the purpose of deployment as an installation, the latter is a problem which does not cause any insurmountable challenges and can thus be ignored in the case of this application.

### 3.2 Inspirations and the Sonification Model

Before breaking down the design of this application, it might be useful to cover some of the vital aspects of the framework of MBS. As indicated by Hermann, Model-based Sonification is a general paradigm for the definition, design and implementation of sonification techniques. A fundamental part of this paradigm is the adoption of a *sonification model,* which can be defined as a specific instance or design achieved with MBS [1]. There are a number of generic *sonification models* presented and elaborated in the handbook. However, pending on the purpose of the sonification and the characteristics of the data, the designer can exercise a degree of flexibility and therefore does not need to uphold a strict adherence to the latter model.

As with this system, the adopted sonification model and its subsequent intuitive design are based on and inspired by the exemplified sonification models found in the various and plentiful projects carried out by Hermann, T. and others. These are summarized below:

- The **Particle Trajectories in a Data Potential** model, whose aim is to *receive information about the clustering of vectorial data,* specifies the use of data points as fixed places (or *planets)* within the data space, each of which *contributes to a global data potential,* or *a gravitational force,* imposed on the model space. The model space also features probing particles which are subject to this "gravity", and whose interactions in turn are set to *approximate a harmonic potential*. I.e. as the particles get close to the fixed data points (or planets) the harmonic oscillations of pure tones increase, and as they drift further away, they diminish [10].

- The **Data Sonogram** model specifies *the use of one virtual mass-spring system per data vector in a model space of the same dimensionality as the data space.* The user excites this model by creating a virtual shockwave of a desired speed and magnitude, which disseminates through the model space, dislocating the mass-spring systems from their state of equilibrium, resulting in oscillations (with damping) which in turn produce sound accordingly [11].

- The **Tangible Data Scanning** model features data points represented as localized mass-spring systems, much like the Data Sonogram. However, the main difference with the latter is having

the data points dispersed and embedded into the physical 3D space around the user, who then uses a sensory device (*Planar object, like a piece of cardboard*) to *scan* this space, exciting the data points' attached mass-spring systems as they come into contact with the sensory device and thus producing sonifications [12].

- In the **Principal Curve** (machine-learning algorithm) sonification model, each data point in the data space links to a distinct sound source which contributes to the overall soundscape. The user/pointer moves along the specified curve through the data space and can only hear respective sonifications of data points which are located on the curve, as it passes them by [13].

Inspired by the *Data Sonogram* model*,* the author has chosen to adopt the use of an array of interconnected mass-spring systems in virtual 3D space, which functions as the main point of gestural articulation of the sonification by the user. The length of this array is equal to the length of the data vector[1] array (one mass-spring system per data vector). In contrast, in addition to the lack of a shockwave for excitation, this array (or sheet) of mass-spring systems, while having some data-driven physical properties (length of springs, mass of points, stiffness, damping, etc.), does not directly connect data values to their sonifications. Instead, much like the sensory device in the *Tangible Data Scanning* model, it is responsible for providing a controller for human interaction; with the main difference that unlike TDS, this human interaction controller functions in the virtual 3D space, as opposed to the physical 3D space around the user.

Finally, inspired by the *Particle Trajectories in a Data Potential* and the *Principal Curve* models, the data vectors (*N* data points of *d* dimensions) are dispersed in the same virtual 3D space alongside the said array of mass-spring systems, with the XYZ coordinates of each point being fixed and mapped to the data vector (similar to the "planets"). Moreover, each data point has a one-to-one proximity relationship with each mass-spring system. The resulting array of distance variables is directly mapped to the sonification parameters. In other words, the closer each mass-spring system gets to its corresponding data point, the

1. Data vector here refers to a list of floating point, fold-change values per measured protein/RNA, in discrete time-periods over the course of the Mass-spectrometry Proteomics Analysis experiment. See Figure 1.

more perceivable processing results in the sonification for said point. The contrast between this model and the *Principal Curve* is the lack of the calculated curve which determines a singular path for the movement of a pointer (in this case the mass-spring array) through the model space. Instead, the user can explore the entire virtual 3D space freely and without restriction.

### 3.3 The Data

Another important reason/inspiration for adopting the above sonification model is the underlying data type being high-throughput and high-dimensional. The particular dataset used in this system, features 9524 data vectors (measured proteins) of 4 dimensions, expressed in binary logarithmic, fold-change form. This data is acquired as part of the Mass-spectrometry Proteomics Analysis experiments, in which all the proteins within the cell sample are measured as the sample is introduced to the induction/removal of an oncogene. **Appendix Table B. 1**, demonstrates a snippet of this dataset. Other similar experiments may produce similar datasets with a varied number of both throughput and dimensions. The use of the *Log2* function in expressing protein fold-change measurements is desirable and common in such experiments, as these measurements would then be neatly represented as negative and positive values centred around 0, denoting respectively, down-regulation and up-regulation in protein expression.

| Protein Index | 12hrs_Log2(Oncogene OFF/ON) | 24hrs_Log2(Oncogene OFF/ON) | 36hrs_Log2(Oncogene OFF/ON) | 48hrs_Log2(Oncogene OFF/ON) |
|---|---|---|---|---|
| **1** | 0.151547 | -1.10219 | 1.18763 | -0.86689 |
| **2** | -0.0507698 | -1.2263 | 0.733113 | -0.468267 |
| **3** | -0.0627022 | 1.2203 | 1.3548 | 0.887139 |
| **4** | 0.0158854 | -0.256123 | -0.835385 | -1.25104 |
| **5** | -0.148351 | -0.241301 | 0.468242 | 0.0580604 |
| **6** | 0.080265 | -0.790139 | 0.583954 | 0.0400841 |
| **7** | 0.378796 | -0.35472 | 2.02235 | -0.0973704 |
| **8** | 0.105474 | 0.485986 | -0.330463 | -0.0719597 |
| **9** | -0.328603 | -0.838825 | 0.169767 | 0.117093 |
| **10** | -0.162345 | 0.588433 | -1.26508 | -0.0670884 |
| **11** | 0.6496 | -1.35532 | 1.20024 | -0.361724 |
| **12** | 0.135667 | -0.294527 | 0.777793 | -0.287145 |
| **…** | … | … | … | … |
| **9524** | -0.113268 | 0.0206387 | -0.671347 | -0.205847 |

Appendix Table B. 1 – Protein Log2 Fold-change Data in 12-48hrs Oncogene Removal Mass-spectrometry Analysis Experiment

As with the broader context of Proteomics Analysis experiments and the mentioned produced datasets, the focus is to obtain a holistic image of all protein/RNA activity within the cell as it undergoes the

transformation from a normal state to a malignant one. This is known as a *systems level understanding* of the biochemical processes within the cell [14]. Therefore, the use of an array of interconnected mass-spring systems, each element of which corresponds to each data point and in turn produces a distinct sonification on a discrete audio channel, seemed logical. The resulting sound-world is described and elaborated further in this paper.

The main issue in using the above dataset is the presence of a time index. Since MBS incorporates a dynamic model which changes and evolves in its own time domain, the fact that the data also features time-based evolution of values, can become problematic. This is why MBS is rarely used as an analysis tool for time-indexed data since it is the most difficult scenario to canonically decide what to map to the sonification time [1]. Nevertheless, to tackle this issue for musical purposes, the aforementioned sonification model for this application essentially omits the time-index by the linear mapping of sequential fold-change values to XYZ coordinates respectively, which is similar to and inspired by the hierarchical clustering of high-throughput datasets. This also bears an important link to the aim of the *Particle Trajectories in a Data Potential* sonification model, mentioned earlier, and can be regarded as an important strategy in representing salience within the underlying dataset. In fact, various data clustering algorithms and software are often used by cancer scientists in order to reduce the high dimensionality and volume of measurements in Mass-Spectrometry Proteomics Analysis experiments, so that practitioners can analyse such data for patterns, similarities and spikes with significantly less difficulty and time consumption [15].

In other words, in this sonification model, through the aforementioned mapping of data values to virtual spatial coordinates, those proteins/RNAs that have similar fluctuation patterns will fall closer (cluster) together in the 3D space, and therefore produce similar sonifications.

**3.4 Sonification**

As mentioned previously in the examples of musical sonification frameworks, the use of electroacoustic techniques and a focus on spectromorphological concepts of sound [6] can be a useful methodology in

the sonification of complex and multi-dimensional data. This is a shift from the use of elementary, notation-based musical concepts such as pitch, interval, chord, rhythm, etc. commonly used in the design of sonification systems; which is perhaps due to their convenience, simplicity and familiarity, that make them altogether an efficient and coherent platform for the sonification process. As the purpose of this application is to achieve a high level of electroacoustic musical and aesthetic complexity, a similar focus on the spectromorphology of sound, and Pierre Schaeffer's concept of the *sound object* is adopted [16]. This compositional outlook, as Carla Scaletti points out, creates a fundamental base for the formation and manipulation of discrete sonic elements (*timbre*, *pitch*, *duration, amplitude, gesture, etc.),* under a *uniform abstract structure,* perceived as a whole [17]. This also bears an analogous relationship to the high-throughput dataset used in this sonification system, and the idea that each protein's fold-change values are responsible for the manipulation of specific sonic parameters, which in turn give voice to that protein (sound-object) next to all the others (sound-world), is prevalent.

*3.4.1 Mapping*

Based on the aforementioned sonification model, the mappings to sonic parameters of the sound objects result from both the data space and the model space in combination. For instance, the movements of the mass-spring array contributes to the overall gestural characteristics of the sound-world based on human interaction, while the timbre, pitch and amplitude of each sound object result from the data-points embedded in the 3D space and their variable distance to the mass-spring systems.

Moreover, in line with exercising artistic flexibility with the main goal of achieving musical results, the adopted mapping structure is also consequent of a rigorous trial-and-error method with the feedback loop of analytic compositional listening, ultimately aiming for balance between puristicly data-driven and arbitrary sonification.

Some of the key mappings are specified below with regard to the primary synthesis technique used in this application.

*3.4.2 Synthesis*

The principal synthesis technique used in this application is a modifiable granulation/micro-montage of a sample pool of any number of audio files. The reason for this choice stems from the same analogous relationship between the high-throughput dataset – which paints a holistic picture of the cell's protein activity – and the concept of the sound object as a composite, elaborated earlier. This analogy is dominant in the choice of the concatenation of data-driven sound grains contributing to a broader auditory gestalt. However, it is worth noting that the size of the sample pool bears an inverse relation to performance, as does its diversity in terms of source audio files, to interpretability and coherence of the produced sonifications. Furthermore, this granulation is implemented separately on discrete audio channels using the multichannel capabilities of Max/MSP version 8, which facilitates its instantiation as many modifiable granulizers on distinct audio channels. Its sonic parameters are mapped to the combined (union of) sets of data values, data-points embedded in 3D space and the mass-spring array. In other words, each protein's measurements (data-vector) are responsible for its distinct sonification, in relation to its fold-change values and the overarching gestural input from human interaction. Another important benefit of using the multichannel capabilities of Max 8 is the spatialization of each protein voice with respect to the position of the camera (user's POV) in the GUI. This can ultimately allow the sonification audio to be projected in a multichannel ring of loudspeakers of any desired number, in order to create a sonically immersive experience for the user. Finally, as a result of the modularity of Max/MSP objects and programming, various other synthesis techniques can be implemented and used with this sonification model in addition to granular synthesis.

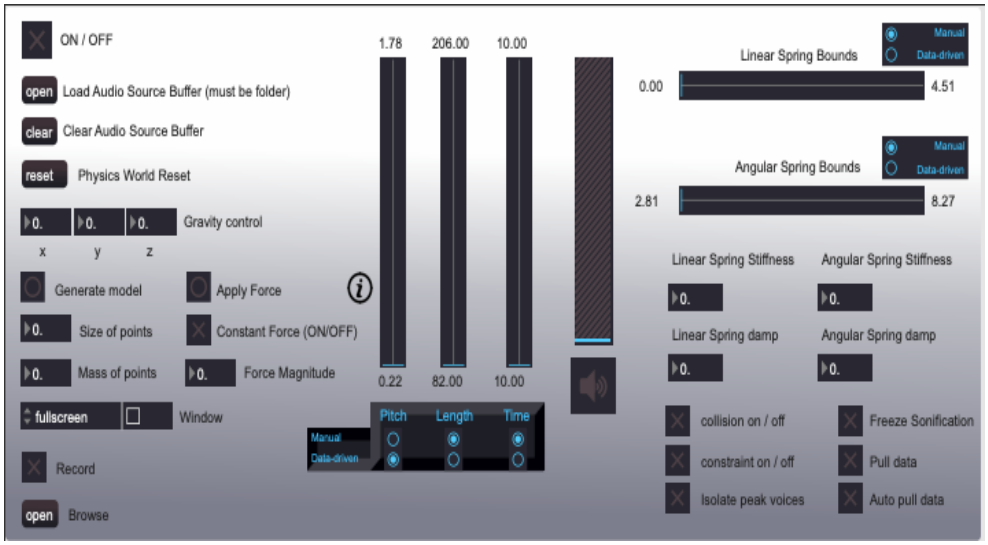
With regard to notable mappings, the central tendency (Geometric Mean) of each protein, i.e. the activity level (up/down- regulation), is mapped to the ID of source audio files; effectively deciding which sound file goes into the source buffer of each granulizer. Therefore, by having an ordered set of distinguishable sounds, for instance gamelan hits ordered in pitch from low to high, the resulting sonifications will sound low in pitch for less active and high for more active proteins. The central tendency parameter is also mapped to the ranges of *grain-generation* rate, *grain-transposition* and *grain-length* as well as the ranges of key physical parameters of the mass-spring array.

Moreover, the amplitude envelope parameters of *decay, sustain and release* are mapped to the variable distance of each embedded data point to its respective mass-spring system; while the *attack* and *grain generation rate* are mapped to velocity of the mass-spring systems. This ties the gestural and timbral qualities of each sonification to both the data and the human interaction element, which effectively also creates an intuitive and natural sound-world based on the physical aspects of sound and movement. I.e. when the mass-spring array is excited more intensely, the resulting sonifications will be louder and more granulized and when static, the sounds die out.

## 4. Operation

### 4.1 GUI & Interactivity

The graphical user interface consists of two main sections: the animation window, and the control interface. The animation window allows for two main visual modes of interaction with the model space. I.e. the movement of the mass-spring array by click-and-drag using the mouse pointer or touch on touchscreen display, and the movement of the camera by the keyboard's W, S, A, D, Q and A, or *drive* keys (for forwards, backwards, left, right, up and down respectively). The control window provides the user with basic model setup, i.e. loading of the sample pool, turning on the audio, initiating the model, volume control, etc. In addition, to foster more freedom in interactivity, the user can exercise control over the ranges of sonic parameters of the sonification as well as the physical parameters of the mass-spring array, such as *spring bounds*, *stiffness, damping,* a uniform *mass* for all mass-spring systems, or switching on/off collisions and/or the springs between masses altogether. In other words, the user can tweak both the sonification, and the interactivity - which inevitably feeds back into the sonification –, if they choose to, or simply allow these to be directed by the data. Furthermore, the user has the option to excite the model using a randomised (constant/impulse) force at any modifiable intensity as well as enforcing a modifiable gravity force onto the entire model space. **Appendix Figure B. 1**, provides a screenshot of the Control Window (interface), and its subsequent control parameters.




Appendix Figure B. 1 – Musical Model-based Sonification Control Window

The aforementioned controls were included in the design with the goal of increasing musical interactivity so that a variety of musical gestures could be achieved by the user. For instance, the dragging motion results in sustained sounds whilst using the impulse force to excite the model, can produce sharper and more *staccato* sounds. Also, as briefly covered before, the intensity of the user's interaction with the model (velocity) results in sounds with a variety of amplitudes and granularities. For instance, by dragging the model while increasing/decreasing the velocity, the user is able to produce *crescendos/decrescendos* in amplitude and texture; and with the manipulation of the sonic parameters as well as the choice of the pre-loaded audio sample pool, the user is able to exercise control over the overall timbral qualities of the sound-world.

### 4.2 Data frames

Due to the high-throughput nature of the data and the immense number of measured proteins -7000 to 10000 measured proteins per experiment-, a scope of focus has been implemented in the sonification process which limits the number of data vectors being sonified at all times. I.e. the user can pull a frame of 80 proteins at each turn to be sonified. The main reasons for this design choice are avoiding overly complex and arbitrary sonification, as well as meeting computing resources' limitations, e.g. memory and CPU/threads. This is also similar to the work of Diniz N., et al. mentioned earlier, whose design also

allows for only a limited number of data points from the entire underlying dataset to be sonified by the user at each moment [7].

In this sonification system, when each data frame is pulled by the user, there are perceivable, static onset changes in the visual and auditory characteristics which result from a shift in the camera angle and background colour for the visual, and as previously discussed, from the mapping of data values to the ranges of parameters of both the model space and the sonification, for the auditory. These onset changes, respective to each data frame, result in a *resetting* of the behaviour and characteristics of the model and effectively set a new auditory/visual scene for the user to explore. The use of the term "auditory scene" is not coincidental here and bears reference to the Auditory Scene Analysis process of Albert Bregman.

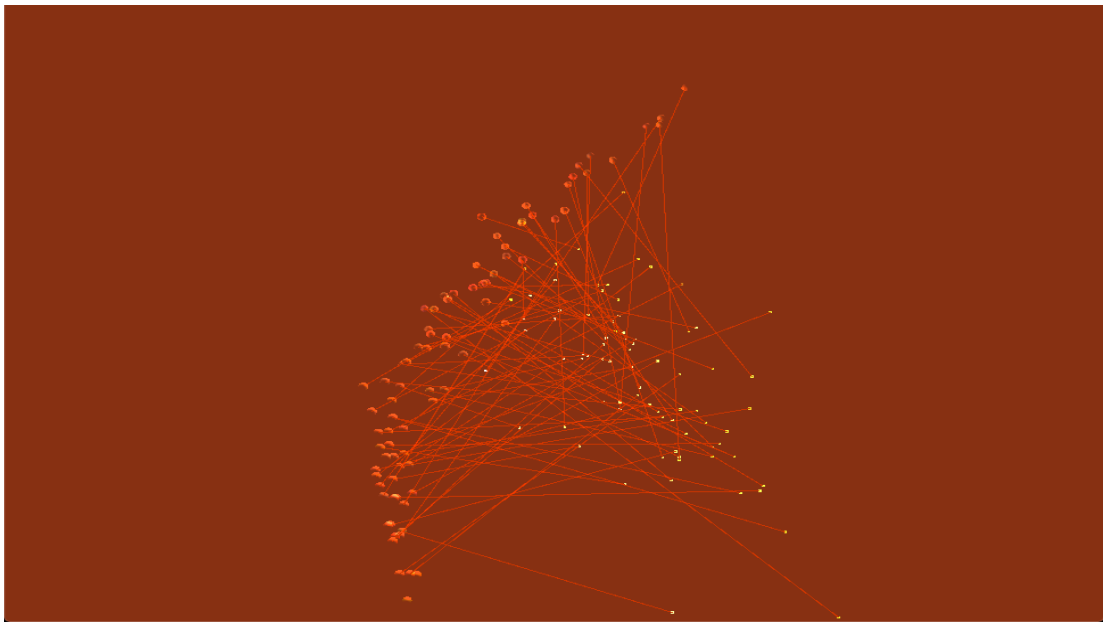
To summarize, Bregman indicates that our brains have evolved the natural ability to perceptually analyse, segregate and recognize complex sounds within a mixture by applying both the primitive process – innate phylogenetic identification by various acoustic clues from the sound -, and the more complex, schema-based recognition. In the latter, we can use contextual information acquired through preparation or prolonged exposure to the sound mixture, in order to successfully segregate its components. In that regard, Bregman's test subjects performed better in recognizing patterns (tunes or melodies) which were regulated or repeated in the mixture with only marginal variation over the course of the experiment. Bregman compares this varied repetition to how things would be in a musical context [18].

Although not a primary goal in this project, the design of this system, particularly the use of granulation which incorporates grain repetition, in theory gives chance to data-driven patterns to emerge from the sound-world in a regulated manner, during the course of the time that the user is exploring each data frame. Thus, giving the ability to their auditory system to attempt at creating the learned schema required for the segregation and recognition of said patterns. Moreover, the modifiable sample pool, also allows the user to retain a specific set of sounds throughout the sonification of various data frames, therefore increasing the overall contextual learnability of the model. However, it must also be reiterated here that the choice of overly complex input audio files for the sample pool, can result in obscuring the

mentioned patterns and consequently also the relationship between the sonifications and the underlying data.

### 4.3 Animation

The animation of the GUI is implemented using Max/MSP's jitter physics objects. These objects create a world and multiple rigid bodies within it which are bound by the laws of physics. The animation maintains a simplistic and minimal design, using only generic spheres, with invisible springs in between for the mass-spring systems, and bright dots for the embedded data-points. Furthermore, there are visible line segments stemming between each data point and its respective mass-spring system, highlighting this fundamental link in the sonification model. **Appendix Figure B. 2**, provides a snapshot of the animation window.



Appendix Figure B. 2. – Musical Model-based Sonification Animation Window

### 4.4 Compatibility with other datasets

As Hermann points out, MBS is indifferent to the semantics of the underlying dataset. This is one of the important reasons why it is such a useful approach to data sonification as opposed to parameter-mapping [1]. In other words, it does not matter to the model and the sonification it produces what the

data values mean in terms of the broader context in which they were acquired. The same holds true for this application and in theory, with little modification, the user can input any high-throughput, tabular dataset, featuring data vectors of at least 3 dimensions. Therefore, this sonification model can also be extended as a general framework for such data.

## 5. References


[1] Hermann, T., Hunt, A. and Neuhoff, J., 2011. *The Sonification Handbook*. Berlin: Logos Verlag, pp. 399-427.

[2] Gresham-Lancaster, S., 2011. Relationships of sonification to music and sound art. *AI & Society*, 27(2), pp. 207-212.

[3] Bresin, R., Hermann, T. and Hunt, A., 2012. Special Issue on Interactive Sonification. *Multimodal User Interfaces*, [online] 5(3-4), pp. 85-86. Available at: https://doi.org/10.1007/s12193-012-0095-7

[4] Hermann, T., Höner, O. and Ritter, H., 2006. AcouMotion – An Interactive Sonification System for Acoustic Motion Control. In: S. Gibet, N. Courty and J. Kamp, ed., *Gesture in Human-Computer Interaction and Simulation*. Berlin, Germany: Springer-Verlag Berlin Heidelberg, pp. 312-323.

[5] Maes, P., Leman, M. and Lesaffre, M., 2010. A Model-Based Sonification System For Directional Movement Behavior. In: *Proceedings of ISon 2010, 3rd Interactive Sonification Workshop*. Stockholm, Sweden. [online] pp. 91-94. Available at: https://interactive-sonification.org/files/ISon2010_full_proceedings.pdf

[6] Smalley, D., 1997. Spectromorphology: explaining sound-shapes. *Organised Sound*, [online] 2(2), pp. 107-126. Available at: https://www.cambridge.org/core/services/aop-cambridge-core/content/view/S1355771897009059

[7] Diniz, N., Deweppe, A., Demey, M. and Leman, M., 2010. A Framework for Music-based Interactive Sonification. In: *The 16th International Conference on Auditory Display (ICAD-2010)*. Washington, D.C, USA. [online] pp. 345-351. Available at http://www.icad.org/icad2010/icad2010.pdf

[8] Wilson, S., Vasilakos, K., McCauley, T., Khosravi Mardakheh, M., Margetson, E. and Yeung, T., 2020. Sonification of High Energy Physics Data Using Live Coding and Web Based Interfaces. In: *Proceedings of the International Conference on New Interfaces for Musical Expression (NIME'20)*. Birmingham, UK. [online] Available at: https://www.nime.org/proceedings/2020/nime2020_paper76.pdf

[9] Cycling74.com. n.d. *What Is Max? | Cycling '74*. [online] Available at https://cycling74.com/products/max

[10] Hermann, T., & Ritter, H., 1999. Listen to your Data: Model-Based Sonification for Data Analysis. In G. E. Lasker & M. R. Syed, eds. *Advances in intelligent computing and multimedia systems*. Windsor, Ontario: Int. Inst. for Advanced Studies in System research and cybernetics, pp. 189-194.

[11] Tunnermann, R. and Hermann, T., 2009. Multi-touch interactions for model-based sonification. In: *Proceedings of the 15th International Conference on Auditory Display*. Copenhagen, Denmark: International Community for Auditory Display. [online] Available at: http://www.icad.org/Proceedings/2009/TunnermannHermann2009.pdf

[12] Bovermann, T., Hermann, T. and Ritter, H., 2006. Tangible Data Scanning Sonification Model. In: *Proceedings of the 12th International Conference on Auditory Display*. London, UK. [online] Available at: https://www.icad.org/Proceedings/2006/BovermannHermann2006.pdf

[13] Hermann, T., Meinicke, P. and Ritter, H., 2000. Principal Curve Sonification. In: *Online Proceedings of the 6th International Conference on Auditory Display*. Atlanta, Georgia, USA: International Community for Auditory Display. [online] Available at: https://www.icad.org/Proceedings/2000/HermannMeinicke2000.pdf

[14] K. Mardakheh, F., Z. Sailem, H., Kümper, S., J. Tape, C., R. McCully, R., Paul, A., Anjomani-Virmouni, S., Jørgensen, C., Poulogiannis, G., J. Marshall, C. and Bakal, C., 2017. Proteomics profiling of interactome dynamics by colocalisation analysis (COLA). *Mol. BioSyst.*, [online] 13(1), pp. 92-105. Available at: https://pubs.rsc.org/en/content/articlehtml/2017/mb/c6mb00701e

[15] Beer, I., Barnea, E., Ziv, T. and Admon, A., 2004. Improving large-scale proteomics by clustering of mass spectrometry data. *Proteomics*, [online] 4(4), pp. 950-960. Available at: https://doi.org/10.1002/pmic.200300652

[16] Schaeffer, P., 2004. Acousmatics. In: C. Cox and D. Warner, ed., *Audio Culture*. New York: The Continuum International Publishing Group Inc, pp. 76-81.

[17] Scaletti, C., 1989. Composing Sound Objects in Kyma. *Perspectives of New Music*, 27(1), pp. 42-69.

[18] Bregman, A., 2001. *Auditory Scene Analysis*. Cambridge, Mass.: The MIT Press, pp. 395-453.