Cyberactions and Cyberinstruments via Physical Modeling Synthesis: Extending Musical Realities

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A Dissertation presented to the Graduate Faculty
of the University of Virginia in Candidacy for the Degree of
Doctor of Philosophy

McIntire Department of Music

University of Virginia
May 18, 2008

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ACKNOWLEDGEMENTS

I would like to thank to my adviser Judith Shatin who has guided me through the process of writing this dissertation. Her critical and insightful suggestions continuously provoked new ideas and refinements. Special thanks go to Stefania Serafin, my external reader, who has introduced me to and patiently taught about physical models. Thank you to my dissertation committee, colleagues, family and friends for their support and enthusiasm and to the University of Virginia for kind and generous assistance during my studies.

ABSTRACT

This dissertation focuses on physical modeling synthesis, and argues that this synthesis, rooted in physical action, can serve as a key to connect music-making processes in the physical world to those in virtual worlds. In the physical world, we create music via mechanical action. In some music, mechanical action motivates the creation of all aspects of composition, including its conception, form, instrumentation, instrumental design, performance and score. I call such music "action-based." I will begin with a consideration of perception and the role of mechanical action in this arena. I follow this with a consideration of the history and techniques of physical modeling, showing how this type of synthesis can be used in the following dimensions: imitation, augmentation and hybridization of existing sound sources, as well as facilitating novel sound-production mechanisms. I also describe how "cyberinstruments" extend musical realities in my own compositions.

INTRODUCTION

In chapter one, I review the field of aural ecological perception and provide a general background regarding our hearing of mechanical actions in the physical world, and particularly, in music. I then define action-based music which foregrounds mechanical action in a global approach to composition, including its conception, form, instrumentation, instrumental design, performance and score. Simulation of actions through physical modeling synthesis brings action-based music into the virtual world, and here I suggest a topology of cyberactions which replicate, extend, hybridize and distill the principles of these mechanical actions.

I introduce physical modeling from both the historical and technical points of view in chapter two. I detail the particular structural and functional characteristics of different physical modeling sub-techniques such as digital waveguides, modal synthesis and mass-spring-damper algorithms, as well as the general design principles which apply to all types. I also review a number of software applications in which physical models have previously been implemented.

Finally, I discuss my own work in the third and final chapter and describe how extended, hybrid and abstract cyberinstruments enabled me to build a continuum between physical and virtual realities. I detail the formal organization, scoring, design of software interfaces and the modeling

approaches in pieces that use traditional instruments, ethnic instruments, everyday objects, musical toys and cyberinstruments. I show how mechanical action underlies my creative language, facilitating a discourse between physical and virtual musical realities.

CHAPTER 1: THE LANGUAGE OF ACTION-BASED MUSIC

1. Introduction

This chapter discusses action-based music in which mechanical actions form the principal means of musical expression. I begin with an inquiry into how we hear and identify mechanical actions in the physical world, and particularly, in music. I then show how the music of some twentieth-century composers, such as Russolo, Cage, Lachenmann and others embodies action-based music derived from instrumental mechanics. I then trace the roots in electroacoustic music and propose a topology of cyberactions. In conclusion, I suggest that physical actions can be mirrored, expanded, transformed and abstracted in cyberspace via physical modeling synthesis.

2. Ecological Perception

In his seminal work *The Senses Considered as Perceptual Systems* (1966), James J. Gibson, the founder of ecological psychology, proposed a novel approach to perception based on the detection rather than sensation of the information in the everyday world[1]. The observer acquires information about any environment through a set of higher-level variables including

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[1] Ecological psychologists and psychoacousticians such as, W. Gaver (Gaver 1993a and Gaver 1993b), J. Neuhoff (Neuhoff 2004), D. A. Norman (Norman 1988) and others later developed Gibson's propositions.

energy, ratios and proportions. When these are detected, the observer identifies what Gibson has termed their *affordances*, or opportunities, functions, and values—in short, the relationship between the abilities and needs of the observer and capacities of the environment (Gibson 1966). For example, an observer strikes an object, which resonates to inform the perceiver about its "hollowness". This property suggests that this object may allow "filling" (Windsor 1995).

According to Gibson, orientation, exploration, and investigation of the senses in the environment enable the perceiver to recognize the invariants, the environment's permanent characteristics. Such exploratory activities suggest obtained—as opposed to imposed and passive—perception. Perceptual systems, which include nerve centers at various levels, thus actively seek and extract information from the flowing array of ambient energy in the environment (Gibson 1966).

Gibson contends that selected information is perceived as a whole, not as a series of component elements, so that an analysis of those constituent elements will not yield the information about perception. For example, we do not perceive the actions of individual neurons when grasping objects with our hands. Agents of mechanical action, such as component joints, are organized in the hierarchy of the whole, which hierarchical orders are fundamental to our perception. As Gibson writes,

> The smaller units are embedded in the larger units by what I will call *nesting*. For example, canyons are nested within mountains; trees are

> nested within canyons; leaves are nested within trees; and cells are nested within leaves. There are forms within forms up and down the scale of size. Units are nested within larger units. Things are component of other things. They would constitute a hierarchy except that this hierarchy is not categorical but full of transitions and overlaps (Gibson 1979, 1986, 9).

The forms perceived by humans are of human scale and so are the durations of the events. In short, in the ecological approach to perception, information is considered to lie in the structure of energy (its arrangement, or array), whether that is light or sonic vibration, which informs the observer about the affording properties of the event/object. Environments, therefore, can be regarded as being composed of a myriad of potential stimuli. Information is perceived as a whole, rather than a series of elements. An observer is able to perceive hierarchically ordered events within his/her spatial and temporal range. Consequently, different observers, depending on their needs and sensitivities, will pick up different stimuli in the same environment. Perception is therefore an active process of seeking information, while orientating and attuning oneself towards the source; *affordances* provide opportunities for action.

3. Application Of Gibson's Theory Of Ecological Perception To Hearing

In the area of aural modality, the British ecological psychologist William Gaver makes a distinction between *everyday* listening and *musical* listening to explain the ecological approach to perception. The essential difference between everyday and musical listening lies in the listening experience and not the sounds themselves. Gaver observed that people describe the sounds they hear in terms of their sources:

> Your experience of hearing 'a single-engine propeller plane flying past' is an example of *everyday listening*, the perception of sound-producing events. The experience of 'a quasi-harmonic tone lasting approximately three seconds with smooth variations in the fundamental frequency and the overall amplitude,' on the other hand, is an example of *musical listening*, the experience of the sounds themselves (Gaver 1993a, 387).

Consider the example of a squeaking door, and in particular an observer's aural perception of it from the ecological point of view. A perfectly oiled door would make very little sound and thus would be difficult to identify as such. How do we identify the sound of a squeaking door? What does the sound afford?

Upon detecting any sound, we tend to orient our body towards the sound source. We do that in order to attune our hearing mechanism to the emerging sound. Once positioned, we study the sound's energetic structure to decode the information it contains.

A sonic event is a result of an action followed by the energy transfer (Kendall 1991). Door squeaking suggests a mechanical action, in which an energetic stimulus sets a suspended rigid body in motion. This action is framed as a continuous gesture developed in space and time. From the gesture's profile, we can estimate the door's motion trajectory, material, size, shape, weight, age, the spaces it separates and even the emotional charge the action may be impregnated with. For example, a quick squeak followed by a slam may be identified with abrupt and high-energy emotion, while a slow cracking sound may suggest an unnerving feeling. However, is the sound that of the door being opened or closed?

What the door squeak affords to a particular listener depends on the listener's position, i.e. their individual needs, sensitivities and attention. Furthermore, relating the sound events to the physical events is a process learned in the early childhood. (Kendall 1991). While one observer may identify such a sound as signaling entrance, others may associate it with departure, crossing or passing. Yet, to others the sound may afford the idea of aging!

The most important ecological question we instantaneously evaluate is, however, the source: how do we know that what we heard was indeed the door squeaking? That is, what made the door squeak? We know that the lack of lubrication in hinges causes friction, defined by basic physics as an obstruction to movement in any mechanical system. We can identify squeaking as a true sonic example of friction in action, with shaped frictional squeaking in particular suggesting an obstructed and dysfunctional door. Such noise is extremely useful to our perceptual capacities: not only does it point to the sound source's characteristics, but it verifies the source's actuality. We hear and know that there is a moving door in the space.

We can find similar verifications in music. Consider a frictional sound native to music: a scratch tone—the exaggerated friction sound of the bow scraping across the strings on a bowed string instrument. The scratch tone reveals to us that something must have gone terribly wrong while producing the normal sustained bowed string sound (particularly when positioned in a close proximity to a normal bowed tone). We direct our attention to the production mechanism to examine the malfunctioning action. Metaphorically, the string needs oiling! We ponder whether this can be achieved by tweaking the performer's hand and arm or adjusting the bow position, speed and pressure. Or plainly: does somebody here need more practice? In any case, we understand something about the string instrument in question: we can recognize it in various performative modes which reinforces our recognition of the instrument.

Now, what if such sounds were musically explored? For instance, if repeated, can an isolated scratch tone create a musical pulse? Can it be paired with other performative actions such as bowing on the bridge and the body of the instrument to generate a musical context? Can such sonic vocabularies construct an expressive language? The following section entertains such propositions.

4. Action-Based Music

As stated in the introduction, action-based music emphasizes the artistic exploration of instrumental actions which are used to control all aspects of composition, including its conception, form, instrumentation and instrumental design, performance and score.[2] Actions applied to sounding objects, musical instruments and actions of environmental phenomena thus can become the principal means for musical expression. The composer prioritizes exploration of performative actions as opposed to the investigation of particular sonic parameters in the creation of such music.

In a simple example, a composition rooted in the action of rolling is conceptually action-based. The form of the composition can be derived from the decelerating shape and pacing of the rolling gesture. Instruments used to perform such pieces may include Bocci balls, bicycle wheels, percussion mallets or uniquely designed rolling mechanisms. The composer explores and, most excitingly, transforms actions. A composer can transform the intensity, duration and geometry of a rolling motion in his/her compositional process. Altering the excitation mechanism and rolling surfaces can result in the creative development of the rolling action. The composer can similarly alter the type of action, as by transforming rolling into bouncing. The score of

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[2] Instances of such pure action-based music are difficult to locate, but there is some music which engages action in profound way as described later in the chapter.

such a composition would perhaps consist of specific diagrams, graphic icons and verbal instructions which explain *what to* perform.

While performing action-based music the player is, in fact, often instructed about *how to* and *what to* perform rather than what sonic effect they are supposed to achieve. Graphical choreography of actions in the notation often mirrors the physical movement of the performer. (The graphical gesture of a circle, for instance, will suggest circular motion of the arm on the instrument, as detailed in the chapter three.) The performer's contact with the instrument is thus often embedded in action-based music's notation.

Russolo, Cage, Kagel, Fluxus musicians and Scratch Orchestra associates were among the first to develop graphical and verbal instructional choreographies which suggest musical actions.[3] Concert music composers such as Berio, Crumb, Lachenmann, Ligeti and Sciarrino have also developed instructional languages which combine traditional notation with verbal and graphical directions. As opposed to the graphic notations that symbolize the type of sounds to be produced (e.g. in music of Brown and Penderecki), the notations of these composers tend to suggest a choreography of movements to be performed.

[3] While Fluxus event scores also consist of verbal recipes, scenarios, proposals, propositions and instructions about the desired performative actions, the instructions are often not specific and the pieces lack development. An example of a Fluxus event score is described later in the chapter.

In physical terms, the bow can initiate a performative movement as shown in my previous example; a hammer and air can stimulate other actions. Strings and bores are the resonating media in which actions develop. Whereas some actions involve sustained excitation, others require only a single gesture. Action is continuously developed on vibrating structures such as bowed strings, which need a constant energy supply in order to sustain a sound. On the other hand, an initial energy stimulus will set a self-sustained oscillator, such as a bell, in motion.

We can group actions involving two rigid objects into the following categories: bouncing, bowing, hitting, plucking, rolling, rubbing, scraping, cutting and shaving. Dripping and pouring suggest fluid bodies in action. Blowing means that air initiated the action. Shaking and stirring can combine liquids and solids. Such musical vocabularies have their own morphological characteristics, but they can all be considered part of one language: the language of action-based music, the topology of which is displayed in the following figure.

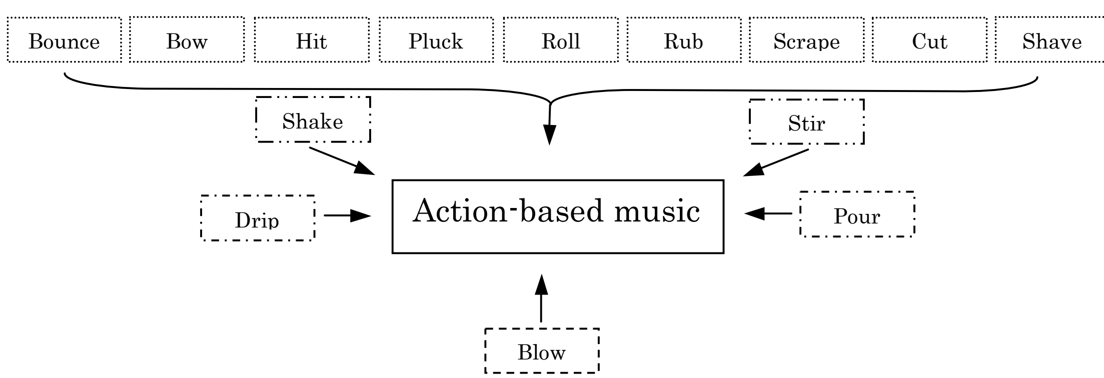

Figure 1. Action-based music and its lexica.

Establishing, sustaining and developing actions create the musical content. The syntax of action-based music governs the formulation and order of all-encompassing performance techniques. In the time domain, the focus is on dynamic rhythmical arrangements which result from the inherent motion of physical gestures. In terms of sonic qualities, temporally dynamic spectral morphology is the principle music parameter of action-based music. Pitch is often concealed in the colored noise which highlights actions.

4. 1 Action: Acoustic Inquiries

Action-based music has possibly developed from music which integrates extended instrumental techniques. In some kinds of folk music, such as Roma music, actions such as string scratching, detuning, retuning, tapping on the body and all *sul XXs* are frequently used as expressive musical tools. In pre-twentieth century Western concert music, such techniques were engaged only rarely and only to achieve a special effect. Notable examples include the *col legno battuto* in the fifth movement of Berlioz' *Symphony Fantasique* (1830), the *flautando* in Debussy's *L'Apres-midi d'un Faune* (1892-94) and the *sul ponticello* in the first act of Puccini 's *Madame Butterfly* (1904).

A number of early 20th century composers developed new instrumental techniques and introduced a spectrum of novel timbres. For instance, Luigi Russolo and Edgar Varèse embraced the sounds of daily actions. In his 1913 Futurist manifesto *The Art of Noises*, Russolo (1885—1947) proposed that the sounds of mechanical actions were to define the music of the new era (Russolo 1913, 1986). With Ugo Piatti, Russolo constructed twenty-one *intonarumori* (intoners or noise-makers)—mechanical simulations of the sound production mechanisms that produced daily sounds as shown in figure 2. This family of instruments included howlers, roares, cracklers, rubbers, bursters, gurglers, hummers and whistlers, forming the futurist orchestra.

These unique mechanical instruments were accidentally destroyed in a fire during World War II, and due to Russolo's early death, only some of them were later replicated for the Russolo-Pratela Foundation in Varese. Russolo did not document the exact mechanics of his *Intonarumori*, but it is understood that all the instruments involved a metal sound-projecting horn and wooden box that hosted the sound production mechanism. Some of the instruments, such as the *Croaker*, involved a tooth wheel striking a string. The performer was able to control the speed of the wheel and the string tension with a crank attached to the instrument. Increasing the rotational speed of the wheel resulted in a sound with higher density and amplitude, while increasing the string tension with a lever controlled the pitch.

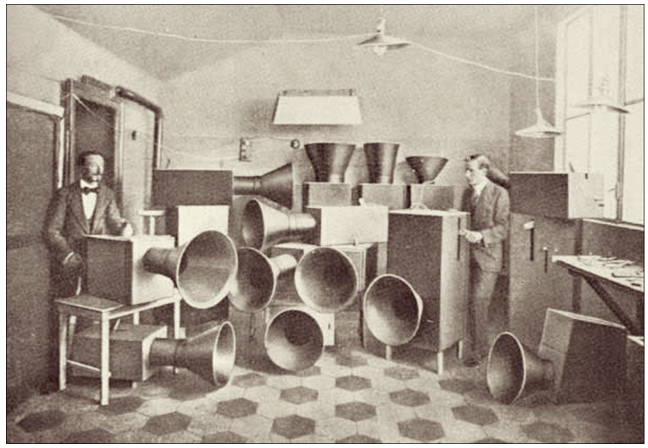

Figure 2. L. Russolo, U. Piatti and *intonarumori*. Image originally published in *Art of Noises* (Russolo 1913).

Russolo showed the enormous potential of choreographed action as a tool for creating and performing music. His instruments suggested a variety of performative actions, such as grinding and operating a handle, scraping and plucking. Russolo's notation went beyond the conventional notations of his time as it combines musical parameters such as meter and dynamics with action parameters such as rotational speed of the crank and lever position as shown in the figure 3.

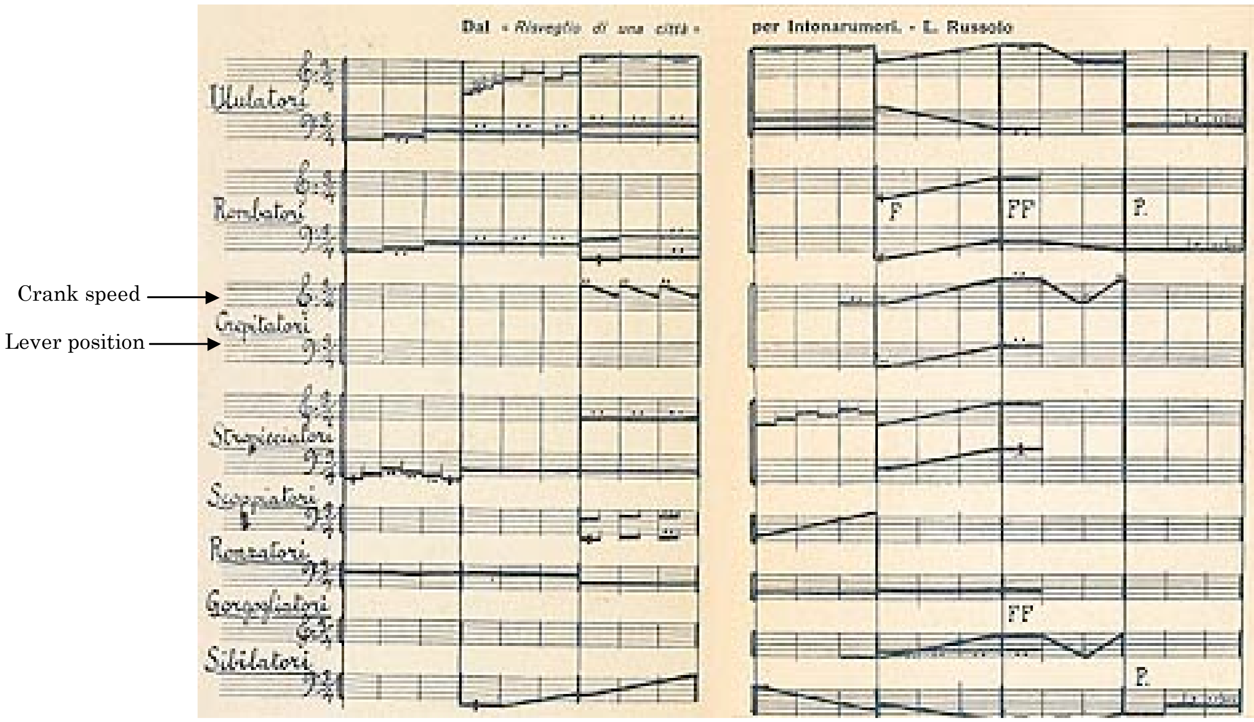

Figure 3. An example from Russolo's *Risveglio di una città* (*Awakening of a city*). Note the lever position and speed rotation in *Crepitatore*. The notation combines musical and action parameters. Image originally published in *Art of Noises* (Russolo 1913).

John Cage (1912—1992) also believed in 'musicalizing' all actions, and specifically in composing with both everyday objects and music instruments. Inspired by Marcel Duchamp's ready-mades, Cage often proposed as musically valid the manipulation of 'non-musical' found objects. In his lectures, Cage exposed sounds of speech and noisy actions such as coughing, snoring or laughing sounds as timbrally captivating musical objects (Shultis 1995). Action often defined Cage's performance and composition. Cage's scores often detailed the description of actions or the lack of them. In the original "Woodstock" version (1952) of his well-known composition *4'33,"* Cage used empty music staves to notate performer's inactivity. Research claims that this lost score resembles A. Allais' 1897 *Funeral March* (Solomon 2004). In his 1953 revision, Cage curiously deleted the original musical staves to perhaps embed action (or inaction more precisely) in the notation. The following figure compares the two notations.

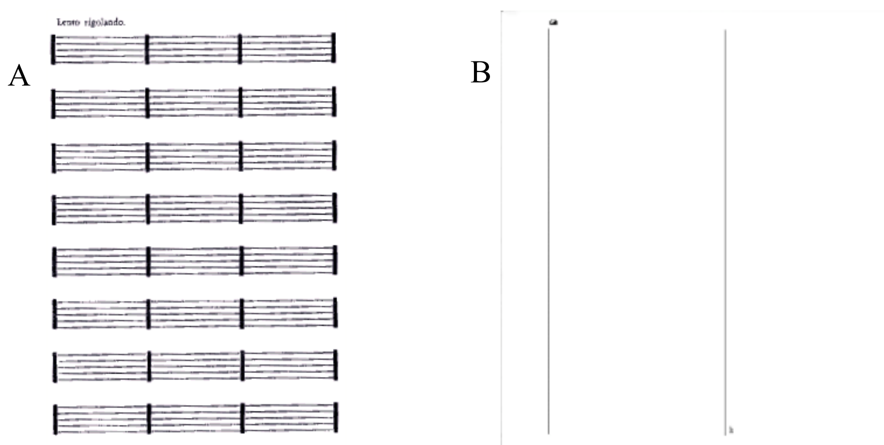

Figure 4. (A) The score of Allais' *March Funebre* (originally printed in 1897; reprinted in *Oeuvres posthumes*; Allais 1966) which looks like the lost original of Cage's 4'33" and (B) Cage's "Kremen" edition of 4'33" (originally published 1953; ©Edition Peters.).

In his 1960 composition *Water Walk*, Cage performed with a variety of kitchen devices and appliances to create a musical composition. The composition involved found objects defined as musical instruments, and a variety of performance stage actions, as shown bellow.

Figure 5. Cage in action performing *Water Walk* on CBS popular TV show *I've Got A Secret* (January 1960). Images acquired from www.youtube.com.

While Russolo used novel mechanical instruments and Cage used daily actions in musically meaningful ways, George Antheil (1900—1959) combined existing instruments with daily objects to hyperbolize mechanical actions in music. In 1924, Antheil composed *Ballet Mecanique*, a composition for three xylophones, four bass drums, a tam-tam, two pianos, a siren, three airplane propellers, seven electric bells and sixteen synchronized player pianos. The mechanical parts were in fact so complex that the piece could not be performed in its original form until the utilization of the computer controlled Disklaviers in 1999. In 2006, the League of Electronic Music Urban Robots, under the direction of Eric Singer, created a version entirely performed by MIDI (Musical Instrument Digital Interface) controlled robots for a Dadaist art exhibit at the National Gallery of Art in Washington, DC. This fully automated installation is a musical celebration of mechanical action's power and expressiveness.

Similarly, Conlon Nancarrow (1912—1997) searched within the constraints of conventional instruments for extreme speed of mechanical actions. He replaced a live pianist with a mechanical player piano in order to make the performances possible. For example, his canonic *Studies* for player piano, which extract atonal and jazz music principles, are a case in point. The resulting extreme speeds and polyrhythmic complexities can be heard as the pure results of music-making mechanisms.

In the early second half of the twentieth century, avant-garde musicians, experimental theater makers and dancers also engaged mechanical actions from their daily lives in art creations. In the 1960s, the New York-based artists of the Fluxus[4] group developed performances, *happenings,* which were an *intermedium* combining art, movement, music and the theater with minimal or no rules (Higgins 1966). The Fluxus "event" scores consisted of verbal instructions about the type of actions to be performed. Action was indeed often the only tool of their artistic expression (Gray 1993). Here is the score of Robert Bozzi's *Choice 15* (1966):

> A performer executes the following actions in succession:
> 1 nails down the great cover of a piano
> 2 plays an extremely extended low note
> 3 strikes the keys with his fists alternating 4 low note strikes with 4 high note strikes
> 4 nails down the keyboard cover
> 5 lifts the end of the piano with the low notes and lets it drop
> 6 kicks at the end of the piano with the high notes
> 7 opens both of the piano covers with the claws of a hammer
> (*Fluxus Performance Workbook* 2002)

Happenings varied in the number and type of performers and media employed, their spatial requirements and their need for an audience. The

[4] This term was coined by Maciunas in 1961 as the title for the anthology of works of the bellow mentioned artists.

Fluxus members Dick Higgins, Bob Watts, Al Hansen, George Maciunas, Jackson Mac Low, Richard Maxfield , Yoko Ono, La Monte Young, Nam June Paik, Allan Kaprow and Alison Knowles performed regularly at various sites within New York City and in their own Fluxhall and Fluxshop (Goldberg 2001).

Like Fluxus, the British Scratch Orchestra based their performances on performative actions, notating their scores with graphics (Parsons 2001). Cornelius Cardew, the leading figure of the orchestra, often notated the general area of potential actions rather than precise individual musical parameters, deriving his imaginary notational systems from traditional notation (Tilbury 1983). Cardew frequently left the interpretation to the performer, as in the following example from his monumental graphical score *Treatise* (1963-1967):

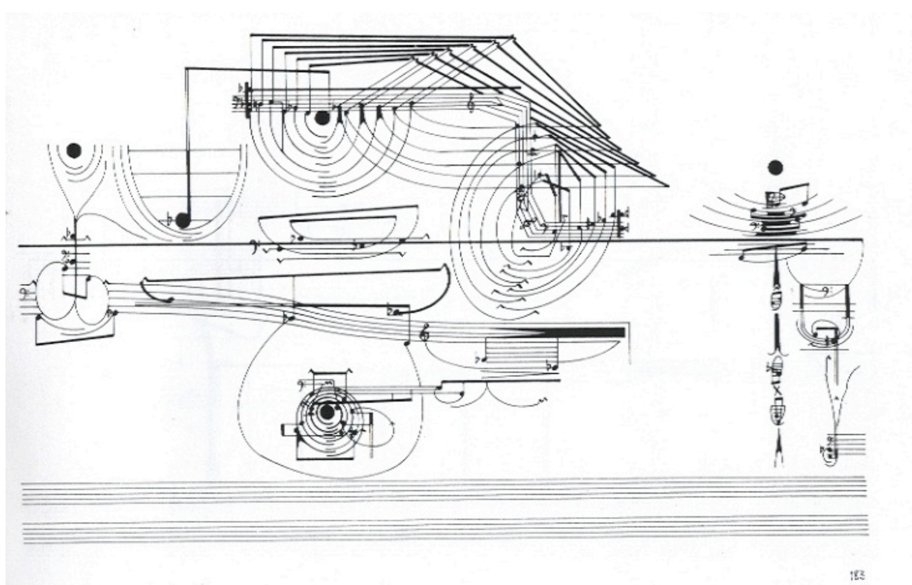

Figure 6. C. Cardew: *Treatise*, page 183. ©Edition Peters.

Both Scratch Orchestra and Fluxus performances frequently employed performers who were not musically trained. While virtuosity did not concern these music makers, composers such as Berio, Ligeti, Lachenmann and Sciarrino composed for musical virtuosos undertaking a multiplicity of performative actions.

Since the 1960s, Helmut Lachenmann (b. 1935) has been connecting the concepts of action and ecological listening in his music. Lachenmann's listening approach is analogous to that detailed by William Gaver earlier in this chapter:

> I hear this [sound] as an energetic process. This way of perception is normal in everyday life. If I hear two cars crashing—each against the other—I hear maybe some rhythms or some frequencies, but I do not say "Oh, what interesting sounds! I say, 'What happened?'" (Steenhuisen 2004, 10).

The question 'What happened?' signifies the composer's deep interest in the physicality of the sound production. Lachenmann has manipulated the sounds of musical instruments without technology developing his *music concrete instrumentale* (instrumental noise). He has invented numerous performative actions with which he dismantles each sound, aurally dissects it, and then recomposes it.

For instance, while the clarinet functions as an airflow filter in *Dal Niente*, *Pression* uses the cello as a transmitter of different types of pressurized noise (Feller 2004). Lachenmann's three string quartets (*Grand*

Torso, Reigen Seliger Geister and *Grido*) present perhaps the most comprehensive encyclopedia of actions executable on string instruments in twentieth century string writing. The actions, not unexpectedly, subvert traditional string performance modes. Lachenmann strives to separately control all aspects of sound production such as bow speed, bow angle and location of the contact point with the string, vibrato, etc.

These actions can be categorized according to their production mechanism into bowed, plucked and hit groups. The first category includes bowing on scroll and pegs, bowing extreme *sul tasto*, *flautato*, *tonlos sul ponticello, tonlos* on the edge of the bridge, *tonlos* on wooden mute, *arco* behind the bridge, *arco flautando* on tailpiece and others. Additionally, heavy pressure and abrupt bow stops produce unmistakable friction sounds such as squeaks and scrapes. Lachenamnn explored plucking the strings with fingers (*pizzicato fluido*, *pizzicato* behind the bridge) and guitar plectra with an unusual variety of intensities, speeds and muting. Hitting the strings with the bow (e.g. *arco battuto, arco col legno battuto* and *saltando*) or the instrument's body produced impact sounds. Such actions are often notated on a separate staff which indicates their location on the body of the instrument. Lachenmann uses traditional staff paper to detail the action parameters as shown in the following excerpt:

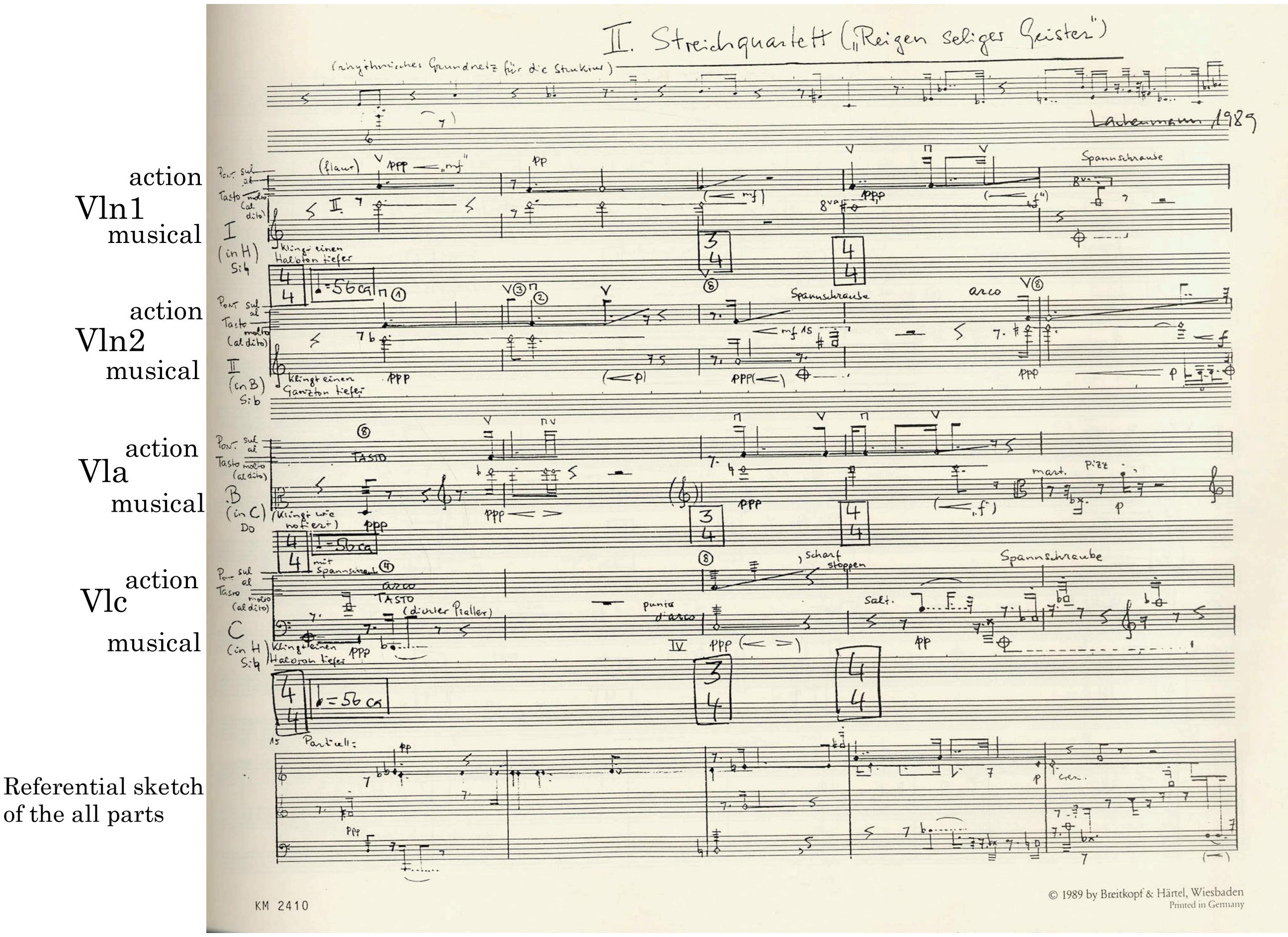

Figure 7. The first page of Lachenmann's second string quartet *Reigen Seliger Geister (Dance of the Holy Spirits)*. Note that each instrument is notated on two staves. The top staff indicates the type of action and its location on the instrument and the bottom staff shows musical parameters. ©Breitkopf & Haertel.

4.2 Actions: Moving to the electroacoustic music domain

Pierre Schaeffer (1910—1995), notably, was also the first to employ the recording of daily actions in music composition. In his well-known *Étude aux Chemins de Fer* (1948), Schaeffer manipulated the sounds of trains to create a musically intriguing context. Interested in the psychoacoustic properties of the sound, however, Schaeffer emphasized the disassociation of the source and cause of any sonic object from sound. Sound objects were to be perceived solely because of their inherent acoustic qualities, not because of the relationship to their source or other extra-musical attributes (Schaeffer 1966). According to the reduced listening of *music concrete,* the listener is expected to avoid any clues that may lead them to the identification of sound sources.

Unlike Schaeffer, Edgar Varèse (1883—1965) organized his sounds from everyday life to be heard as such in his *Poeme Electronique* (1958) for Le Corbussier's Philips Pavilion. Varèse employed recordings of environmental sounds such as bells, sirens, snare drum, machine noises, water-like sounds, aviary-like sounds and glass-like sounds. The composer combined rattles, thunder and murmurs with the sounds of female voices and a male chorus to sonically express various stages of the humanity's development as portrayed by P. Agostini's film projections on the walls of the pavilion (Treib 1996). The sounds were electronically transformed, organized into four sections and projected through specifically designed trajectories in the hyperbolic paraboloid space of the Pavilion[5] (Cabrera 1994). Varèse understood that the acoustic properties of sonic objects, which he himself studied intensively, were rich sources for musical expressions and would bring about a new era: that of digitally synthesized sound (Risset 2004).

[5] The Pavilion performance also included Iannis Xenakis' *Concrete PH* (1958), a short music concrete composition, which engaged sampled sounds of cracking, hissing and burning charcoal.

The French researcher and composer Jean-Claude Risset (b. 1938) studied the acoustic properties of sounds produced by brass instruments and simulated some of them using digital technology during his research visits at Bell Labs and Stanford University in 1960s. Risset also synthesized the sounds produced by planes, sirens and engines while endowing them with an unreal quality for his composition, *Computer Suite from Little Boy* (1968). The composer strived to establish an organic relationship between the familiar and unfamiliar, the everyday and the more traditionally musical, the physical and virtual. Risset handled the confrontation of physical and digitally simulated virtual sounds via cross-synthesis, suggesting a perceptual shift which occurs when the processed or synthesized sounds and physical world sonorities meet, overlap, diverge and contrast (Risset 1996).

Using additive synthesis, Risset accomplished the digital simulation of actions in terms of their psychoacoustic properties such as frequencies, amplitudes and temporal behaviors. As in acoustic composition, this method focuses on musical properties of sound such as pitches and rhythms and rather than foregrounding the mechanical actions. The full digital simulation of actions themselves only emerged with the development of physical modeling synthesis.

4.3 Cyberactions

Physical modeling synthesis, enables the digital simulation of sound production mechanisms and their actions. The technique's historical and technical background is detailed in the following chapter, but here it is sufficient to note that physical modeling facilitates the replication of existing mechanisms and their extension beyond the limitations of the physical world. The simulation of actions and mechanisms not existing in this physical reality is also possible with physical modeling algorithms. While it is a matter of time before the efficient methods simulate realistically truthful complex instruments in real-time, present research already provides numerous tools for artistic exploration suggesting the powerful potential of this technique.

According to their level of distillation digitally simulated actions—cyberactions—can be classified as replica-extended, hybrid and abstract, each of which are characterized by specific structures, unique internal functions and possible excitation modes. Actions are either congruent or incongruent with the physical world. The following table summarizes the three types of cyberactions with their respective structures, functions and driving forces.

Table 1. Topology of cyberactions.

Action Type	Example	Structure	Internal function and direction	Forces
Replica Extended	Plucking the string	Fixed Pair: Exciter-Resonator Congruent with physical world	Exciter acting on resonator Unidirectional	Applied as in the physical world and quantitatively extended. Example: prolongation of the contact between the exciter and resonator, unrealistic forces and velocities
Hybrid	Plucking the bell; Belling the pluck; Plucking in parallel or serial the pluck and the bell	Reconfigurable Pairs or Groups of Exciters and Resonators Incongruent with physical world	E.g.: Exciter acting on Exciter on Resonator on Exciter Multidirectional	Qualitative alterations such as changes in energy flow and type
Abstract	Plucking the performer; Belling the formal structure of the composition	Potentially vibrating structures, particles, phenomena Supra-congruent with the physical world	Formalizing principles, ideas and causes Vibrating or still	Transduction of energy to create behaviors and temporally organized sequences

Replica-extended cyberactions are based on simulations of physical processes as observed in the physical world, such as plucking a string. A plectrum (the exciter) and a string (the resonator) are two fixed agents which frame the plucking action. The unidirectional nature of the action is established by the fact that it is always the plectrum which acts on the string. The structure and direction of such an interaction is thus congruent with the physical world. Once modeled, such action can be quantitatively extended. That means that the processes and forces applied to it can cross beyond the limitations of the physical world, as in the case of plucking the string with unrealistic velocity in extreme dynamics. Figure 8 presents a diagram of such replica-extended action.

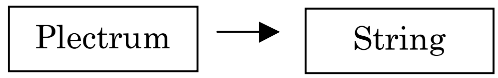

Figure 8. Replica-extended action of plucking a string.

Hybrid cyberactions such as plucking a bell are incongruent with the physical world. Additionally, the exciter and resonator elements become modular in hybrid actions. For example, we can imagine connecting a multiplicity of exciters to other exciters and resonators. Such free order reconfiguration of these components is typical. For example, 'stringing' the pluck suggests a single action in reverse order. Serial, parallel and other modular actions such as plucking-the-pluck-the-bell-the-string as suggested in the figure 9 show the malleable characteristics of hybrid cyberactions.

While extended cyberactions operate with quantitative expansions in temporal and energetic areas, hybrid actions imply the restructuring and partitioning of the energy flow. Such change of focus may result in a variety of unpredictable behaviors such as feedback loops and even gradually decelerating or accelerating quasi-perpetual motions.

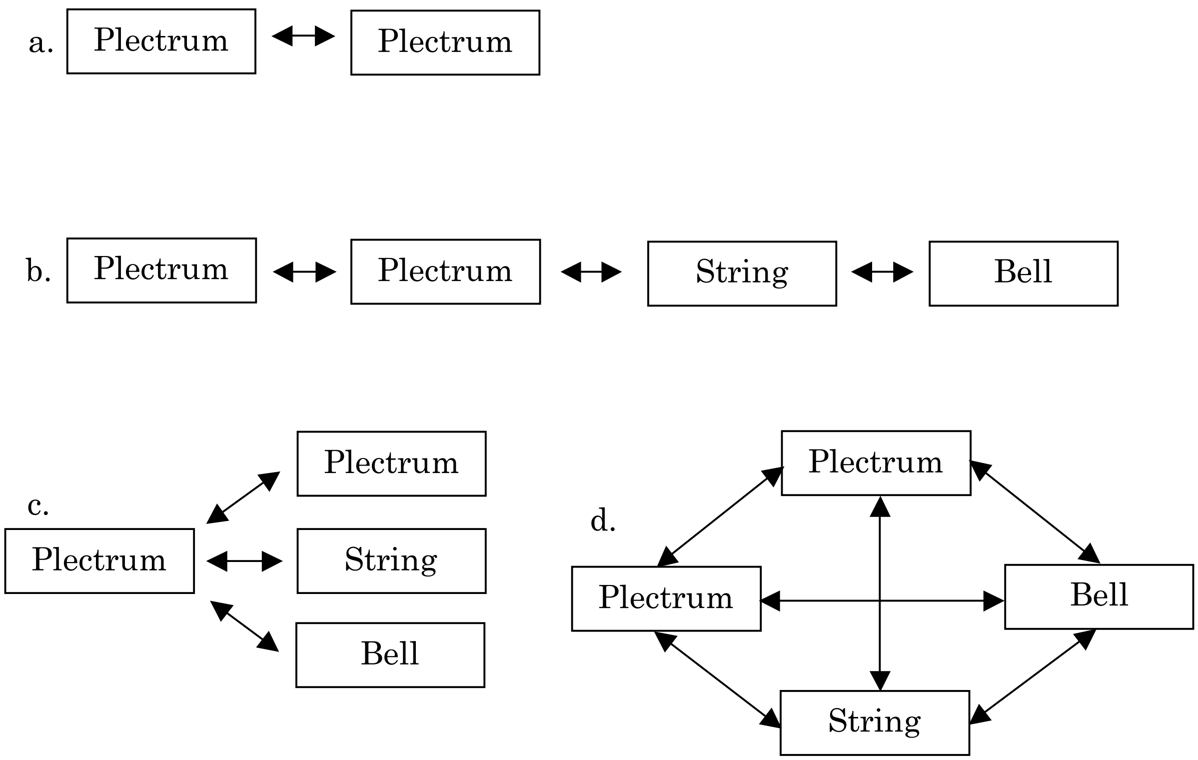

Figure 9. Morphologies of hybrid cyberactions: (a) and multi-member actions in serial (b), parallel (c) and variable order (d).

Abstract cyberactions are the hierarchically most conceptual distillations of physical activities. Plucking the performer and using a bell to form a compositional structure (or 'belling' the composition) exemplify actions in which a potentially vibrating structure initiates and performs fundamental music-making choices. Abstract cyberactions are thus principles, ideas and causes which formalize music creation whether that part of the creation process be composition, performance, or listening. Any possible vibrating structure, particle and phenomenon in its latent and active forms can be a source of action. Abstract actions are supra-congruent with the physical world in the sense that they show both the world's multiplicity and its unity.

As an example of abstract cyberaction, let's take the behavior of a vibrating structure. The pattern propagation along the medium, with its characteristic energy dissipation, gain and transformation, participate in the temporal structure of a composition. Patterned force, velocity, shape, size and other parameters may inform other compositional choices. In its totality, such action can be both composition and performance. Activating other sounding structures with the parameters of the original instrument may also enable a performance.

Figure 10 exemplifies how 'belling', i.e. using a vibrating cyberbell, can foster a complex formalization of the compositional, performative and listening attributes in a music creation. The cyberbell forms the micro, mezzo and macro levels of the cyberaction, manifesting itself in detail, fragment and totality. The energy and behavior extracted from the initial bell, whether it is still or in motion, defines the overall compositional form, conducting patterns, performance behaviors and listening-like responsiveness. The composition remains in an unexhibited state while all the bells are latent. Set in motion, the cyberbells exchange their ecological information such as vibrating patterns, forces and velocities. Such exchange can be facilitated by a conductive pick-up similar to the temperature transfer between molecules, or more traditional links expressed as single actions of hitting, bowing, etc.

As depicted in the figure, the unit Composition ‘bells’ another vibration structure—the Conducting unit via a deliberately placed link. In this process the link’s location and type define the type of energy transfer possible between the two structures. The Conducting unit then adapts the vibrating patterns from the Composition according to its own internal order. The information and energy absorbed by it is then transferred to Performances. Finally, Listening absorbs the complex information from the Performances. The process may stop here, or the energy and information can be injected in any place in the loop.

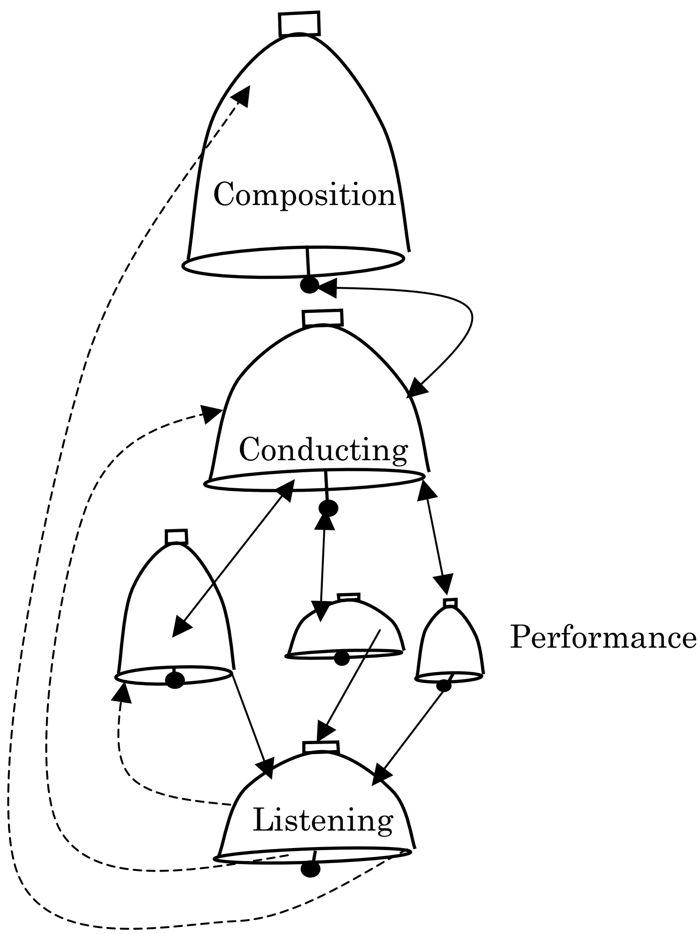

Figure 10. Complex structurally consistent abstract cyberaction of ‘belling’ a music creation.

All aspects of the action share the same sounding structure in our example. The composition, conducting, performance and listening certainly can be of the same type, state of matter (e.g. solid, fluid, or gas), shape, size and material as in the case of a structurally *consistent* action; however, they may also parametrically differ as in a case of *variable* action. The cyberaction may be initiated at any stage, thus abandoning the traditional energy flow between composition, performance and listening. For example, it may be Listening which initiates the vibration and sets the other components of the action in motion. Continuous interaction between the constituent substructures results in feedback and eventual energy dissipation.

All cyberactions are inherently "actual." As Gaver pointed out about perceiving a digital sound source simulated by the physics-based approaches, "listeners comment that they have a strong impression of an actual event causing them, rather than hearing them as synthesized." (Gaver, 2003a) As long as the event bears distinct characteristics of a certain action, the observer will not focus on distinguishing whether a physical cause or a computer produced the sound. As previously described, a scratch tone facilitates recognition of the source, but we may be unaware whether a physical or synthetic instrument produced it.

Actuality in sonic cyberspace is, as in the physical world, dependent on the perception of action itself. It is perceptually unproblematic to validate the actuality of synthetic sources (and, thus, their actions) of the replica type and, to some degree, the extended type as well. Hybrid and abstract cyberactions are derived from the same physical principles, but their perceptual recognition is troublesome, as they often do not refer to any previous aural experience. Ecological perception suggests, that we are unable to perceive events and phenomena beyond our limits. That is to say, our perception is limited to our temporal scale, spatial range and hierarchical order.[6] Extended, hybrid and abstract cyberactions, however, expand beyond such boundaries and orders. They present a challenge which engages designers, composers and listeners in the formation of new perceptual horizons and experiences.

5. Conclusion

In this chapter, I detailed how we hear mechanical actions and how these actions can define an expressive language of action-based music. I investigated the roots of such music in the acoustic and early electroacoustic music domains. I further suggested that action-based music can be mirrored and extended in the digital world through the use of physical modeling synthesis and detailed the topology of hierarchically-ordered cyberactions such as extensions, hybridization and abstract distillations of actions observed in physical reality.

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[6] Accordingly, all virtual displays, whether visual, aural or tactile, are programmed to simulate experiences only within the bandwidths which define individual senses.

CHAPTER 2: PHYSICAL MODELING SYNTHESIS: HISTORY AND RESEARCH

1. Introduction

In this chapter, I review physical modeling synthesis from the historical and design points of view. My discussion focuses on the suitability of synthesis sub-techniques such as digital waveguides, modal synthesis and mass-spring-damper algorithms for the digital simulation of particular mechanical systems, rather than judging the resulting sonic effects. In anticipation of the discussion of compositions based on those techniques in the following chapters, I also suggest musical uses for particular sub-techniques.

Physical models were made possible by historical inquiries to the acoustics and mechanics of musical instruments, and by the development of current modeling techniques. Nineteenth century researchers were intrigued by the study of physics and the potential it offered for the reconstruction of resonating objects, particularly musical instruments. Hermann von Helmholtz (1863), John Tyndall (1875) and Brantz Mayer (1878), among others, proposed and built mechanical models that simulated the behavior of various vibrating structures.

In his 1894 treatise *The Theory of Sound,* Lord Rayleigh described the principles of vibrating systems such as membranes, bars and shells (Rayleigh

1894). Additionally, Rayleigh explained the physics of vibrations in open air, tubes and closed spaces such as boxes. John Fleming's invention of the vacuum tube in 1904 stimulated Steward (1922), Miller (1935) and others to build analog electronic models. However, it was not until 1960s that digital simulations of mechanical sounding objects—physical models as we now know them—were developed (Manning 2004).

2. Definition And Design Principles

Physical modeling enables computer simulations of sonic structures based on the understanding and implementation of their mechanics, something that has been done with musical instruments, environmental phenomena and everyday objects. Physical modeling synthesis has proven to be an excellent vehicle to conceptualize these sounding classes (Borin et al. 1992, Smith 1992).

What differentiates this technique from other synthesis techniques is the fact that physical modeling simulates sound production mechanisms, while other techniques (e.g. additive, subtractive and Frequency Modulation synthesis) model the audio signal as it reaches the ear. For example, it simulates parameters such as frequency and amplitude spectra, which result from the bow—string interaction, when using the synthesis techniques based on psychoacoustic research. The physical modeling approach, however, simulates the mechanics of the bow-string interaction itself.

Vibrating systems such as bowed string and other musical instruments are defined by the interaction between the current external control and still resonating recent activities: the transients.[7] Based on the simulation of physical interaction such as that between the bows and strings, physical models are naturally effective at the refined simulation of transients (Chafe 1989). For example, two identical bowed gestures performed on the same string model —as in the case of a physical instrument—will sound different as the second action interferes with the system that is already set in motion.

These models are simulated using filter theory, implementing vibrating modes and engaging fundamental mechanical agents such as masses, springs and dampers. The resulting models can be fixed or reconfigurable and have been implemented in a variety of real- and non-real time applications.

All physical modeling approaches and implementations share certain general design principles. Gianpaolo Borin, Giovanni De Poli and Augusto Sarti explain that these principles are defined by structural and causal relationships between the physical instruments and their models:

> (1) timbral complexity is determined by the model structure and, as a consequence, by the structure of the algorithm that implements the model; and (2) there exists a precise relationship between the

[7] In sonic terms, transients are sounds which result from the interaction between the new events performed on an instrument with the reverberation of the previous ones.

> reaction of the physical instrument to a certain action, and the reaction of its model (Borin et al. 1992).

The first principle suggests that we choose a modeling approach whose design and sophistication depend on the richness of the timbres of the source. Complex mechanical systems, such as the piano, accordingly involve more intense modeling design than that of a plucked string. Simpler structures have been modeled with clearer sonic resemblance to their physical originals. Simulations of more complex instruments have continually developed, and in instances remain incomplete, with key equations awaiting solution.[8]

The second principle suggests that virtual actions should be consistent with those of the physical world. For example, a string-plucking mechanism should first produce the sound of a plucked string.

The basic design of a physical model begins with the identification of an instrument's physical dimensions and constants in terms of its mass and elasticity, the specification of the boundary conditions (i.e. limiting conditions that cannot be exceeded) and initiate state (e.g. starting performance position), the definition of the excitation mechanism (such as percussion mallet) and consideration for impedence (i.e. resistance to the driving force) and other restricting forces such as friction and sound radiation patterns (Roads 1996, Cook 2002a).

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[8] The accuracy of simulations has been continuously improving. This dissertation does not focus on the perceptual evaluation of the resulting models. Other publications such as Nordahl (Nordahl 2005) discuss the perceptual issues raised by modeled replicas as shown in comparative experiments.

The modeling process continues with the partitioning of a complex model into components which define an instrument's physical, functional and formal characteristics. A violin, for instance, can be subdivided into its basic physical components of strings, bridge, soundboard and bow. The functional description of the instrument is aimed at splitting the sound production mechanism into exciter and resonator zones. Formal description facilitates the separation of a complex model into units according to the degree of simplicity or complexity of the equations needed for its simulation.

The interaction between an exciter and a resonator is vital for physical modeling (Borin et al. 1992). An excitation may be induced by the action of such physical agents as a bow and finger, as in the case of a string instrument. The body of the instrument functions as space, in which the exciter's action resonates. Generally, the exciter displays non-linear behavior, while the resonator acts linearly. String, woodwind and other instruments that produce sound solely during the energy injection are regarded (and modeled) as self-sustained oscillators. Instruments such as a resonating percussion and plucked string that continue to sound (unless damped) after they were excited are considered transient oscillators. Figure 11 shows the subdivision of a basic model's functions and parts.

Exciter
(bow, finger, air, etc.) → Resonator
(strings, bores, sounding board, etc.)

Figure 11. Subdivision of a basic model in terms of functions and parts.

Some modeling sub-techniques are suitable for modeling self-sustained oscillators, while others excel in simulation of the transient oscillators. The following sections detail individual modeling algorithms and highlight their pros and cons.

3. Kelly And Lochbaum Vocal Tract Model[9]

At Bell Telephone Laboratories, J. Kelly and C. Lochbaum designed the first physical model while implementing the mathematical expression of the vocal tract (J. Kelly and C. Lochbaum 1962). The researchers modeled the vocal tract as multiple cylindrical tubes connected with scattering junctions. P. Cook refined the model by adding the nasal tract, neck and gender-defining characteristics (Cook 1991).

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[9] The following materials are further discussed in *Cyberinstruments via physical modeling synthesis: Compositional applications* (Kojs et al. 2007).

4. Hiller And Ruiz Algorithm

Musical instruments such as strings can be modeled using the mass-spring archetype. The behavior of a vibrating string can be mathematically expressed through difference equations which describe the behavior of the digital filters used in the synthesis. Hiller and Ruiz solved the difference equation for a plucked and struck string which enabled simulation of the vibrating string with a series of masses and springs (Hiller and Ruiz 1971).

In the 1990s, Hiller and Ruiz's algorithm was a standard method for the simulation of bowed and plucked strings (Palumbi and Seno 1999). In particular, the non-real-time simulations work effectively as this method is computationally expensive. Models which enable parametrical extensions in non-real time can be usefully simulated with this approach.

5. The Mcintyre, Schumacher And Woodhouse Algorithm

Self-sustained oscillators such as strings and bores may also be modeled with the McIntyre, Schumacher and Woodhouse modeling synthesis. This methodology centers on a detailed examination of the time-domain behavior of sounds, which enables the accurate modeling of such elements as pitch flattening and subharmonics in bowed strings. Coupling nonlinear exciters with linear resonators facilitates the simulation of woodwinds, bowed strings and pipes (McIntyre et al.1983).

The approach is computationally demanding, but effective for more accurate simulation of interaction between the bow and string as it accounts for the width of the bow. Two points located at the outer sides of the bow hair define the boundaries of the bow width. The bowed string simulation is naturally both more realistic and computationally expensive. Chafe used this technique to develop his bowed cello model, which enabled him to augment the properties of the physical instrument (Chafe 1989).

6. Karplus And Strong And Extended Karplus And Strong Algorithms

Karplus and Strong invented an effective algorithm to model a plucked string and drum in 1983 (Karplus and Strong 1983). The simulation begins with a wavetable which is filled with random values. The values are then read and sent to a modifier (e.g. a low pass filter). The algorithm is completed when the data is reinserted to the system and re-read. This process is continuously repeated at high speed. The resulting sound resembles the timbre of plucked string. The following figure shows a diagram of the model.

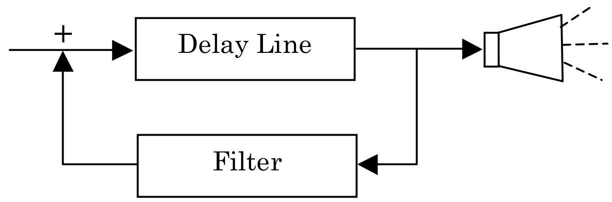

Figure 12. Karplus-Strong physical model (Karplus and Strong 1983).

David A. Jaffe and Smith expanded the Karplus-Strong algorithm by adding filters to the loop. The researchers improved the tuning, control for tone decay time and dynamic, elimination of the initial “plucked” sound, variation of tone loudness in relation to its bandwidth, variation of the character and number of attacks, glissando and slur, simulation of the sympathetic string vibrations, simulation of stiff string and simulation of a moving pick (Jaffe and Smith 1983). Diagram of the extended Karplus-Strong algorithm is shown in figure 13. Charles Sullivan later expanded the algorithm for the simulation of electric guitar string (Sullivan 1990).

The Karplus-Strong algorithm and its extended version are effective and computationally economic techniques for the simulation of plucked strings which can be parametrically extended. Consequently, the model can be implemented in real-time applications. Recently, the model was implemented in PerColate (Trueman and DuBois 2005), which is a free library of physical models for MAX/MSP.

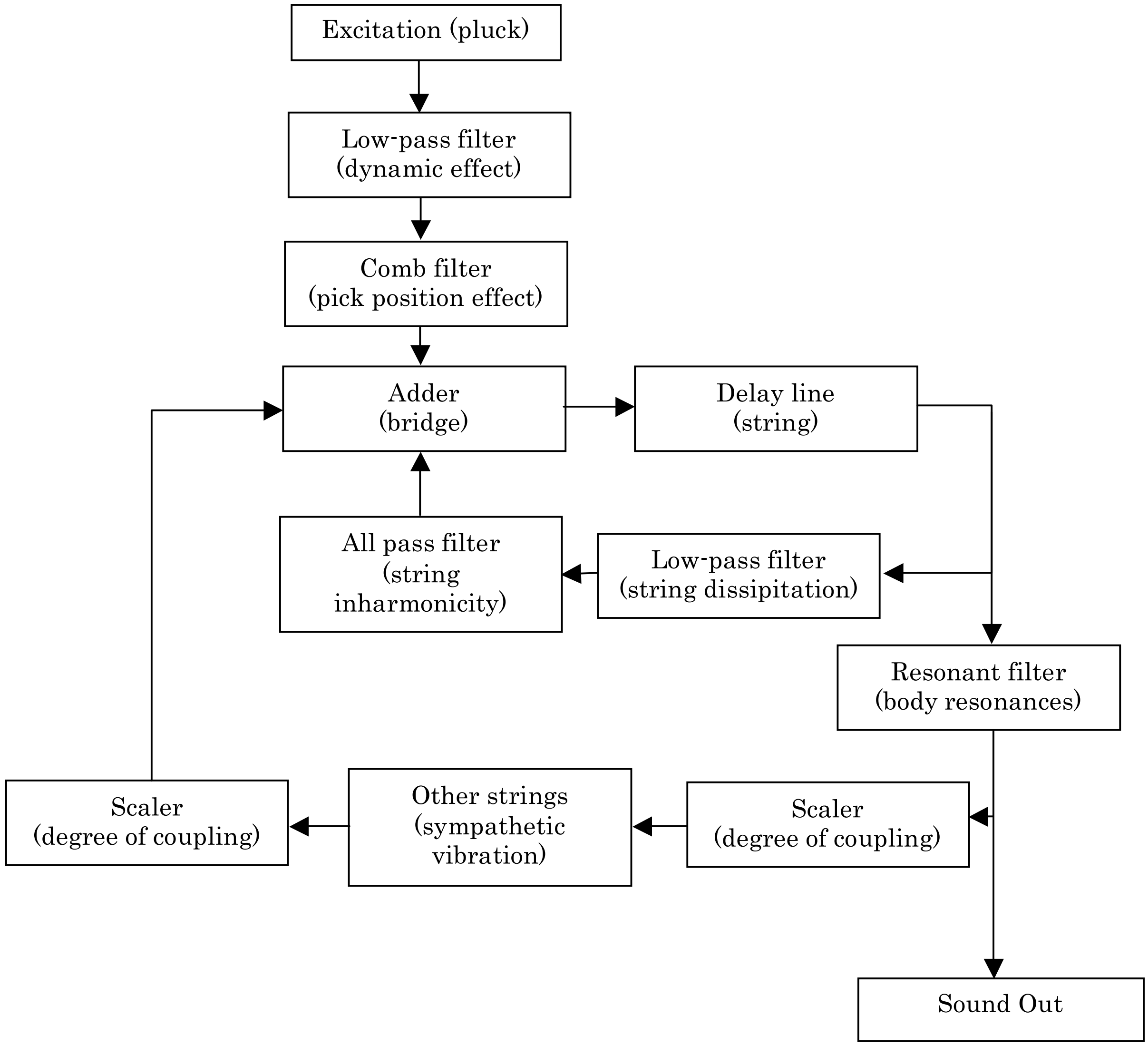

Figure 13. Extended Karplus-Strong algorithm proposed by Jaffe and Smith. The arrows indicate the path of the signal. Diagram adapted from *Orchestrating the Chimera—musical hybrids, technology, and the development of a "maximalist" musical style* (Jaffe 1996).

7. Digital Waveguides

In 1982, Julius Smith introduced modeling with digital waveguides as an approach to physical modeling (Smith 1982, Smith 1983). The focus of digital waveguide synthesis lies in modeling the medium in which the waves propagate. A pair of digital delay lines describes the behavior of sound waves traversing the resonating medium in opposite directions. The interaction of the traveling waves results in resonances and interferences which depend on the medium's dimensions (Roads 1996). Strings and tubes are such media. Figure 14 shows a block diagram of a digital waveguide. The horizontal axis signifies sampling space and vertical axis alignment of the delay pairs. Input in the propagation direction to the right (+) is notated as $y(n)$ and delayed output as $y(n-m)$ where m signifies the sample. The input $y(n+m)$ oriented to the left (-) results in the delayed output $y(n)$. The physical output is a sum of the left- and right-traveling waves given by the following formula:

Equation 1.

$$y(t_n, x_m)= y^{+}(n-m) + y^{-}(n+m)$$

The Z^{-1} elements suggest a delay of one sampling interval. Observation points (positions along the medium) have been arbitrarily placed on points $x=0$ and $x=3X$. X is a distance which the sound travels in one temporal interval T (seconds) corresponding to the calculation of sampling rate $f_0=1/T$ samples per second, where the CD quality sampling is 44100 Hz (cycles per second). Then, $X=cT$ meters where c is the speed of sound, which equals approximately 331 meters per second in air. The spatial interval for sampling is then X= 331m/s*44100s= ca.7.5mm.

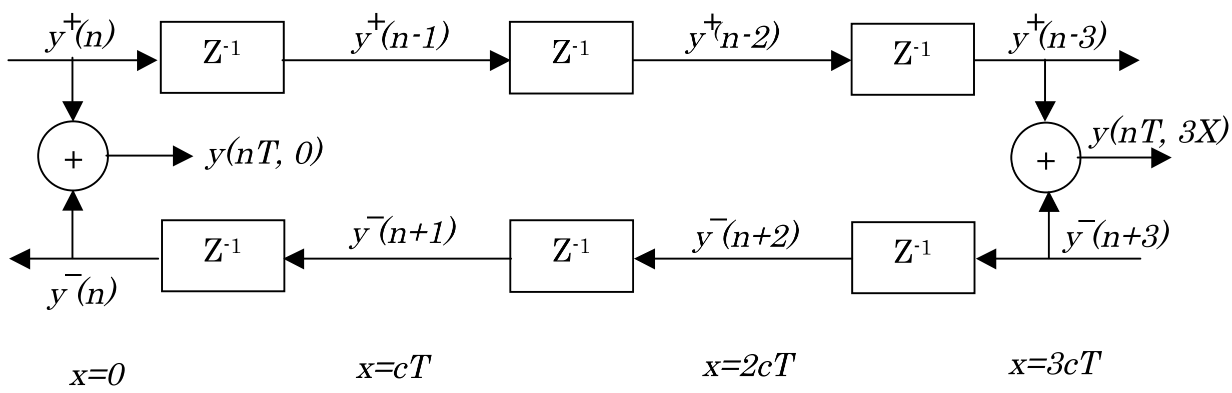

Figure 14. Pairs of delay lines with opposite wave propagation form a digital waveguide. Diagram originally published in *Physical modeling using digital waveguides* (Smith 1992).

If the previous implementation considers an ideal medium, in which no losses occur, other digital waveguides take these losses into account by means of a low-pass filter. Digital waveguides thus offer a greater level of accuracy in modeling vibrating objects. Furthermore, the compactness of its mathematical expression facilitates efficient real-time implementation of the models. In general, systems with quasi-harmonic spectrum such as vibrating strings and tubes are suitable for modeling by waveguides, while inharmonically behaving sonic objects are more efficiently modeled with modal synthesis. In practice, digital waveguides have been used to model a vocal tract (Cook 1991), bowed strings (Smith 1983, Chafe 1989, Serafin 2004), woodwind instruments (Cook 1992, Scavone 1997, Chafe 2005), brass instruments (Cook 1992), a piano (Bensa 2003), a singing corrugated tube (Serafin and Kojs 2005) and *Intonarumori* (Serafin and de Goetzen 2005).

Objects with few inharmonic modes were also modeled using banded waveguides. Examples include resonating percussion bars (Essl and Cook 2000), a musical saw (Serafin et al. 2002a), a Tibetan bowl (Serafin et al. 2002b) and a glass harmonica (Serafin et al. 2002b, Essl 2002). The modeling of highly inharmonic structures is unusual in waveguide methodology, yet Serafin, Huang and Smith proposed a banded waveguide mesh to model bowed cymbals (Serafin et al. 2001). Digital waveguides may also be used for the simulation of hybrid instruments, although this approach for hybrid instrument modeling is less commonplace (Stiefel et al. 2004, Trueman and DuBois 2005). The following figure shows a digital waveguide model of a singing tube.

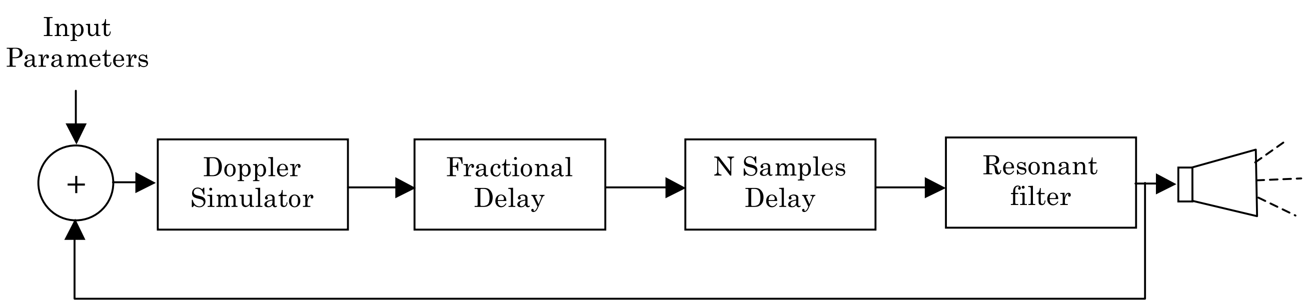

Figure 15. Physical model of singing corrugated tube. Image published in *Computer models and compositional applications of plastic corrugated tubes* (Serafin and Kojs 2005).

Digital waveguides simulate fixed products. Once modeled, the design cannot be altered, but its control parameters can be used to extend the capacities of the modeled objects. The waveguide technique is the most commonly used method for simulation of musical instruments due to the algorithm's compactness and computational efficiency. Waveguides can be used in real-time compositions. While some techniques often require code typing, numerous waveguides were implemented in applications such as MAX/MSP (Puckette 2002, Zicarelli 1998) and Pure Data (Puckette 1996). Both real-time and user-friendly implementations contributed to the increased popularity of the waveguides in the music community.

8. Modal Synthesis

The power of the physical modeling technique lies in its capacity to generate any sounding object without restricting the experimentation to the replications and extensions. For example, an amalgamation of multiple instruments within one object—a hybrid—suggests a higher level of the design distillation. Certain parts of one instrument, such as the bow, are merged with other parts of another instrument, such as a bore, to create a virtual hybrid.

Such hybrids are frequently modeled with modal synthesis (Adrien 1991) which is based on the proposition that any sounding object can be deconstructed into a set of vibrating substructures such as the bridge and body of a violin. Once excited, each substructure produces well-defined modes of vibration. Each mode is represented by its modal data, which consists of its frequency, damping coefficients and shape variables. These modal data may represent structural elements such as a violin bridge, body, string, acoustic bell or timpani membrane. The following figure is a general representation of an acoustical system and its adaptation in modal synthesis.

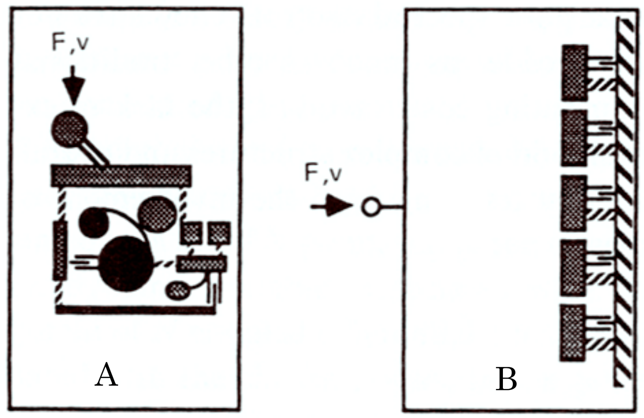

Figure 16. The general modal synthesis scheme. Mechanical system (A) and the vibrating modes of its component parts can be expressed as a set of independent resonators connected in parallel (B). The network uses external driving force *F* and results in combined velocity *v*. Diagram originally published in *The missing link: Modal synthesis* (Adrien, 1991).

The resulting simulation takes into account the elements of all modes involved in the synthesis. The modal synthesis allows the flexibility to reorganize the substructures of the instrument in order to modify its physical (and thus, its sonic) characteristics. Jean-Marie Adrien and Joseph Morrison proposed a computer environment MOSAIC which allows the user to assemble modal substructure objects into musical instruments (Adrien and Morrison 1991). Thus the resulting model is as a collection of mechanical and acoustic resonant structures that vibrate and interact under various excitation conditions. Adhering, striking, bowing and plucking can link the substructures. In some design situations such as connecting reeds and bows to the resonators, it is, however, difficult to set the control values efficiently. Similarly, the debugging and control of spectral features of actual sound is problematic (Morrison and Adrien 1993). G. Eckel, F. Iovino, R. Caussé and other IRCAM-based researchers developed MODALYS, the next generation modal synthesis software (Eckel et al. 1995). This program was later ported to JMAX for real-time realization (Iovino et al. 1999). The MODALYS engine for simulation of physical models *modalys~* is currently available for MAX/MSP.

A still more recent implementation of the modal synthesis can be found in the TASSMAN sound synthesis studio application, which includes a modular synthesizer based on physical modeling synthesis (Applied Acoustics, 2004). Reconfigurable blocks of resonating structures and exciters can be freely connected. Furthermore, this application combines the physical models with other sonic structures and controllers based on the psychoacoustic approach. Figure 17 exemplifies a simple hybrid instrument design in TASSMAN. The resulting timbres depend on the alignment and order of the constituent parts.

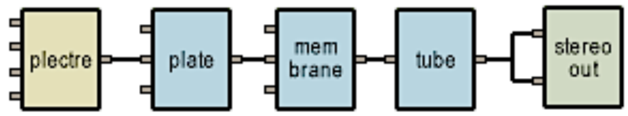

Figure 17. Hybrid model designed with modal synthesis modules in TASSMAN.

Consequently, modal synthesis is particularly well-suited to simulate hybrid structures. Implemented in software such as MODALYS and TASSMAN, the composer works with reconfigurable modules which represent parts. The model can be reconfigured at any time.

9. Physically Informed Stochastic Event Modeling

Extending the principles of modal synthesis, Perry Cook developed the Physically Informed Stochastic Event Modeling (PhISEM) technique which is based on the pseudorandom organization of small sound particles to simulate percussion instruments using numerous stochastically behaving beans. (Cook 1997). Cook's algorithm is based on Newtonian equations that explain the motion and collision of point masses. The statistical principles of particle collision in a shell are applied to simulation of shakers such as the maraca, sekere and cabasa. The following figure shows a diagram of general PhiSEM model.

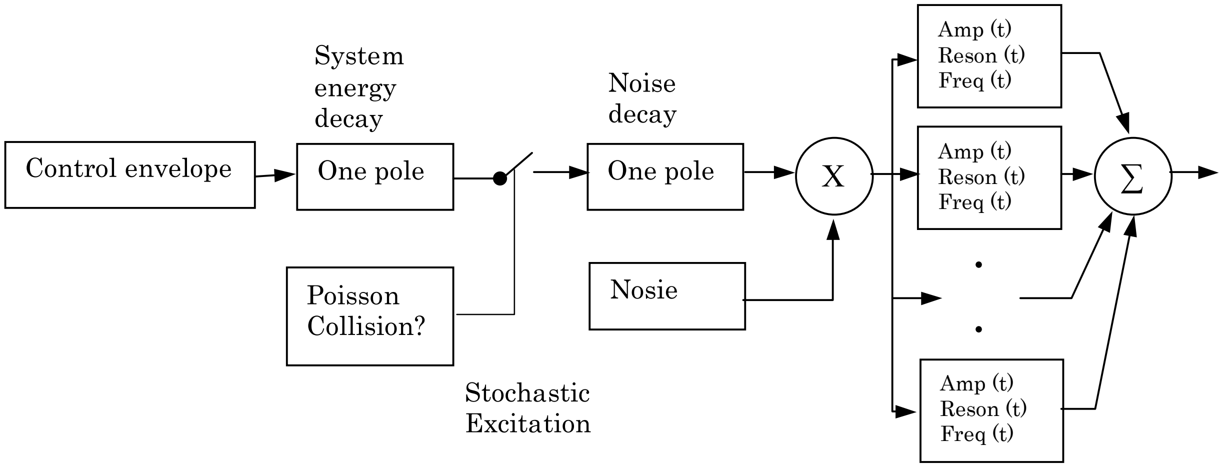

Figure 18. PhiSEM synthesis model. Diagram originally published in *Real sound synthesis for interactive applications* (Cook 2002).

PhISEM algorithm effectively models percussive instruments with a larger number of resonances, such as tambourines and sleigh bells. Individual partials are modeled with digital filters, which resonant frequencies are replaced by another frequency every time a collision occurs. The replacing frequency is located in close, yet random, proximity to the principal resonance. The manipulation of these parameters facilitates the augmentation of the modeled instruments beyond the limitation of the physical world. P. Cook's PhISEM algorithm is most suitable for simulation of percussive instruments, particularly those which engage the movement and collision of such particles (Cook 1997). The models were implemented in a free library of external objects PeRColate (Trueman and DuBois 2005) in MAX/MSP environment. They are computationally inexpensive, which increases their applicability in real-time composition.

10. Mass-Spring –Damper Approach

Borin predicted that taking physical reality as its source of inspiration, 'pseudophysical' models would launch novel explorations in the virtual sonic world (Borin et al. 1992). The 'pseudophysical' models ('abstract models' for the purposes of this dissertation) have materialized primarily through the research of Claude Cadoz and his associates.

The abstract models epitomize the most refined distillation in virtual instrument design, being completely fluid in terms of their inner physics and sonic identities. Although these instruments are also rooted in mechanics, they have no equivalents in physical reality. The limitless possibilities for combining elementary components of sound production such as masses, springs and dampers enables the creation of sonic structures with entirely transcendent virtual topologies.

Such abstract sonic structures have been successfully simulated with CORDIS—ANIMA, an audio-visual environment that epitomizes modeling by combining masses, springs and dampers (Cadoz et al. 1993). Combinations of simpler modules such as masses enable the construction of the sounding object as a network.

The masses and dampers can be connected in a linear system. However, a-conditional link may introduce non-linear behavior to the scheme by establishing an interactive bidirectional relationship between the involved agents. In this arrangement an agent receiving an input such as force will send an output such as displacement. CORDIS simulates the sounds of music instruments, sonic objects and natural phenomena such as moving sand dunes (Luciani et al. 2003), and ANIMA allows the modeling of the visual component.

Within the CORDIS–ANIMA environment, Cadoz and his team recently created GENESIS, a composer-oriented interface designed for building physical models (Castagne and Cadoz 2002). GENESIS facilitates the creation of modular, freely re-combinable, virtual structures and networks. Figure 19 shows the "Triangle" instrument from Cadoz's composition *pico..TERRA* (Cadoz 2002).

The model is constructed of myriad of masses (yellow circles) connected with nonlinear links (blue cords). The blue circle represents masses with a fixed point. The triangle is characterized by its internal network structure and the parameters of the individual components. The instrument is excited by a single mass which can be attached to any point of the vibrating cyber structure.

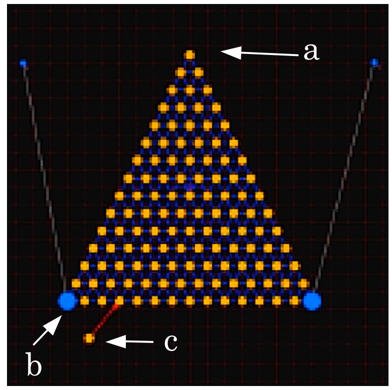

Figure 19. Abstract structure created with GENESIS by C. Cadoz (Cadoz 2002). Masses (a) are connected together in a network “triangle” instrument. Boundary conditions (b) are masses with fixed point properties. The instrument is excited by a single plectrum mass (c). Figure published in *The physical model as metaphor for musical creation “pico..TERA”, a piece entirely generated by physical model* (Cadoz 2002).

The structures can be assigned the functions of instruments, performers and conductors. In figure 20, the abstract structure consists of three model layers: the bell as a conductor (top layer), performer (middle layer) and instrument (bottom layer). All layers are derived from an eleven-mass (yellow color) bell archetype. The types of links and energies that connect the component masses vary. Individual masses of the top layer excite the performer, which transfers the energy to the resonating bottom layer. As the links between the layers can be bidirectional, the hierarchy between the components of this model can become ambiguous. In this particular case, the link orientation suggests that the performer plays both the instrument and the conductor.

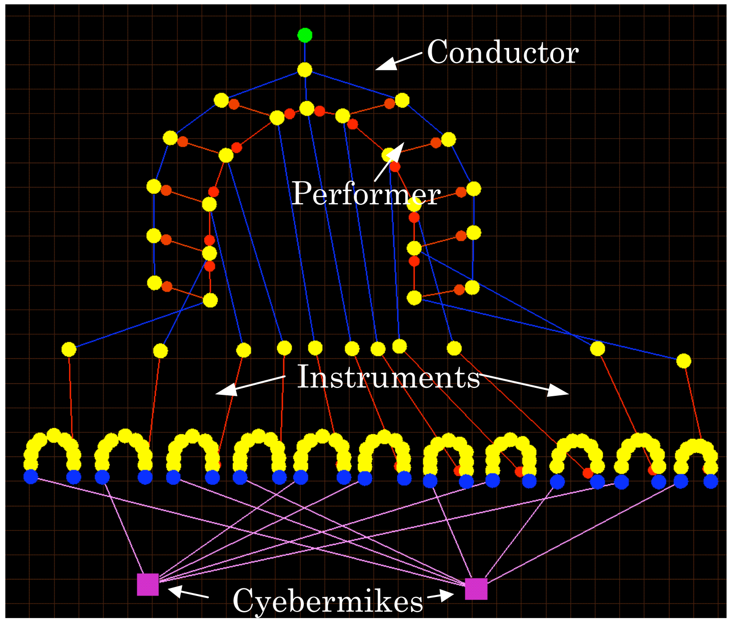

Figure 20. Abstract bell structure: Bells functioning as a conductor (top layer), performer (middle layer) and instrument (eleven bells at the bottom). Models created in GENESIS by J. Kojs.

The conceptualization of musical reality with physical modeling reaches a crossroads where instrument, performance and composition merge. Virtual actions become instruments, and instruments become conductors. The whole compositional process becomes a function of physical behavior simulation. Although currently operating in non-real time, GENESIS is a powerful tool for the creation of abstract cyberinstruments and virtual musical realities entirely based on physical modeling synthesis.

Other applications, which enable the construction of abstract sounding structures are PMPD (Henry 2007) and TAO (Pearson 1996). PMPD runs in real-time. Its developers have recently much improved its functionality, but it still lacks the richness and sophistication of GENESIS. The application TAO was released in 2000. Its development, however, recently stopped.

11. Conclusion

Basing their models on the physical actions of mechanisms, researchers have modeled complex, virtual sonic entities as summarized in table 2. While some techniques facilitate the simulation of self-sustained oscillators, others are effective in modeling transient resonating structures.

Table 2. Details of various modeling techniques and their instrumental design.

Sub-technique	Year introduced	Researcher(s) who introduced the technique	Examples of cyberinstruments designed and designer
Kelly and Lochbaum algorithm	1962	Kelly and Lochbaum	Vocal tract
Hiller and Ruiz algorithm	1971	Hiller and Ruiz	Plucked and struck strings
McIntyre, Schumacher and Woodhouse algorithm	1983	McIntyre, Schumacher, and Woodhouse	Bowed strings (Chafe)
Karplus-Strong algorithm	1983	Karplus and Strong	Plucked string (Jaffe and Smith)
Digital Waveguides	1982	Smith	vocal tract (Cook), bowed strings (Smith; Chafe; Serafin), woodwind instruments (Cook; Scavone; Chafe), brass instruments (Cook), piano (Bensa)

PhISEM: Physically Informed Stochastic Event Modeling	1997	Cook	Shakers such as maraca and cabasa (Cook)
Modal Synthesis	1991	Adrien and Morrison	Hybrid structures
Mass-spring-damper approach	1993	Cadoz et al.	Abstract structures

With the exception of modal synthesis and the mass-spring-damper approach, the design of sounding objects simulated with the most methods described above is fixed. That is, once an instrument has been coded and implemented, it cannot be changed in part or totality. Further, each instrument must be designed separately.

On the other hand, such models, particularly those using digital waveguide synthesis, can be compact, efficient and suitable for real-time use.[10] The waveguides excel in the timbral augmentation of an existing instrument and preservation of their sonic characteristics across registers.

The power of modal synthesis and mass-spring-damper algorithms lies in their ability to simulate freely reconfigurable vibrating modules. While parts of resonating structures such as bridges and boards are the building modules in modal synthesis, the most basic units of a mechanical system such as springs, masses and dampers facilitate the creation of cyberinstruments with the other algorithm. Mass-spring-damper algorithms conceptualizes the sounding reality in the most general terms. Its elementary

[10] The real-time implementation of sophisticated models such as Stefan Bilbao's resonant plates must, however, await more robust technology (Bilbao 2005).

fragmentation gives power to the simulation of *any* imaginable vibrating system.

These algorithms facilitate a higher level of abstraction in the instrument design. The modal synthesis facilitates the simulation of hybrid structures, and the mass-spring-damper approach excels in the creation of the most abstract vibrating forms. The sonic identities of the hybrid instruments emerge from the properties of the amalgamated agents. Abstract instruments enable the internalization of all musical parameters, including their instrumentation, composition, performance and spatialization (Cadoz 2002).

Both approaches have been implemented in compositional environments such as MODALYS, TASSMAN and GENESIS, enabling the composer to become the designer of her/his own virtual instrumentarium without the necessity of direct code typing. Although available to general public, these applications are expensive and some, such as GENESIS, run only on particular operating platforms such as SGI system.

Other programming languages such as C++ and applications such as Synthesis ToolKit (Cook and Scavone 1999), Pure Data and MAX/MSP, with embedded PeRColate library of physical models and ChucK (Wang and Cook 2003), include physical models created with modal synthesis, Karplus-Strong algorithm, digital waveguides and PhiSEM. While some programs enable a non-real time simulation and involve code typing (e.g. C++), others are object-oriented and useful for real-time performance and composition (e.g. PD, MAX/MSP). Some composers have increasingly favored the use of virtual instruments in real-time environments. Such environments are useful to a composer who does not need to be concerned with understanding precisely what happens at various stages of wave production while manipulating the model (Jaffe 1995). Figure 21 displays a physical model of a musical saw designed and implemented in MAX/MSP by Serafin.

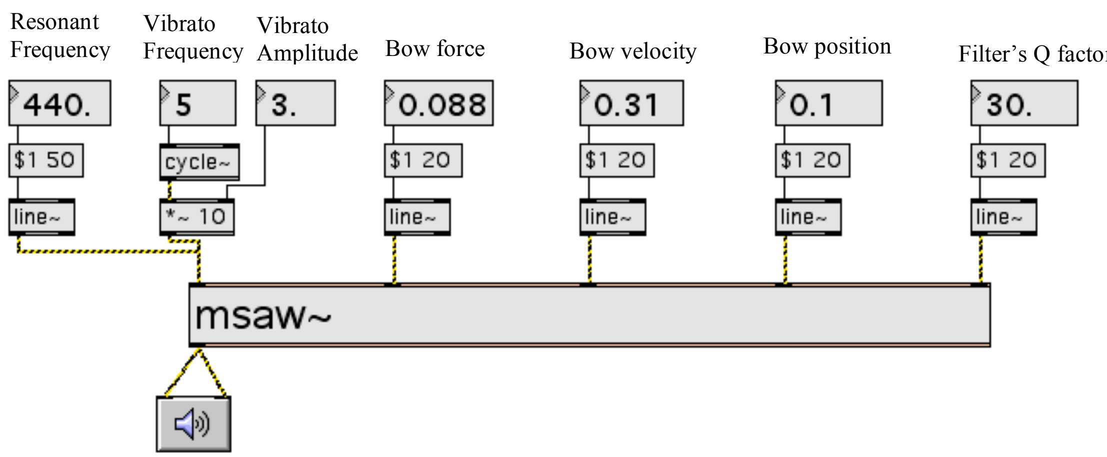

Figure 21. Serafin's physical model of musical saw implemented in MAX/MSP environment.

CHAPTER 3: COMPOSITIONAL PORTFOLIO

1. Introduction

In this chapter, I provide a topology of cyberinstruments based on physical modeling synthesis, and describe how they relate to the action-based music. I detail the various types of virtual instruments used in my own compositions, and explain how I use action as an expressive tool in my music-making process. I also describe compositional parameters such as formal design, pitch, rhythm, timbre and texture. The pieces are grouped according to the types of virtual instruments they utilize, and are organized in chronological order within sections. Except for *Zvonenie* for 4-channel tape, all combine physical instruments such as traditional instruments, Slovakian ethnic instruments and everyday objects with cyberinstruments.

2. Topology Of Cyberinstruments

There are three categories of cyberinstruments: extended, hybrid and abstract which mirror the three categories of cyberactions described in the first chapter. Extended instruments are simulations of existing instruments that augment the instrument's parameters beyond the limitations of their physical origin. A cyberstring, for instance, allows for augmentation of its length, thickness and material beyond the limitations of the physical world.

D. Jaffe used a string as long as San Francisco Golden Gate bridge in his well-known composition *Silicon Valley Breakdown*. Hybrid instruments amalgamate properties of two or more existing instruments such as *ublotar* (Stiefel 2004) and *blotar* (Trueman and DuBois 2005). (These combine the properties of flute and guitar.) Abstract instruments are those inspired by physical laws, yet with no equivalents in the physical world. An example is Cadoz' triangular network of masses and springs in his *pico..TERA* (Cadoz 2002) [11]. Table 3 displays the basic topology of cyberinstruments created by means of physical modeling synthesis.

Table 3. Cyberinstrumental types and corresponding simulated objects.

Cyberinstrumental type	**Modeled object**
Extended	Existing instrument and sonic object
Hybrid	Combination of parts from two and more existing instruments or sonic objects
Abstract	Non-existent instruments and sonic objects resulting from a combination of agents such as masses, springs and dampers.

[11] A further review of compositional applications with cyberinstruments using physical modeling synthesis can be found in (Kojs et al. 2007). In support of this research, I created a website database, www.cybermusik.net, which contains numerous theoretical and musical examples. My own compositions and those of other composers are incorporated. An event calendar, suggested readings and software resources are also listed on the site. For further information on compositions created with cyberinstruments based on physical models by other composers, see Appendix.

As a general rule, any modeling technique can be used to model any cyberinstrumental type. However, practice has shown that some techniques are more suitable for simulation of particular instruments due to their design nature and mathematical effectiveness. While extended instruments are frequently modeled by means of digital waveguide synthesis, modal synthesis is effective in its simulation of hybrid instruments. The mass-spring-damper algorithm facilitates the design of abstract instruments as I show later in the chapter.

3. Extended Cyberinstruments And Cyberactions[12]

I composed the majority of these pieces with cyberinstruments created with digital waveguides (Kojs and Serafin 2008). *All Forgotten* (2006) uses a cybermarimba designed with modal synthesis and *Guiding Night* (2007) uses an extended cyberstring modeled on the Karplus-Strong approach. *Revelations* (2005) and *Neither Stirred Nor Shaken* (2007) use cyberinstruments modeled with both digital waveguides and Physically Informed Stochastic Modeling (PhiSEM). These compositions employ extended cyberinstruments such as the singing cybertube (*Garden of the Dragon* , 2003) bowed cyberstring (*Three Movements*, 2004), cyberfujara (*Air*, 2006), Tibetan cyberbowl (*In Secret* and *En Una Noche Oscura*, 2006), bowed

[12] Materials about the compositions using digital waveguides are further discussed in *Augmenting Sonic Reality. Cyberinstruments Designed With Digital Waveguides* (Kojs and Serafin 2008).

cyberbar (*Revelations*, 2005) cyberflute (*Concealed*, 2006) and percussion cybermembrane (*There He Waited*, 2006).

Performers on musical instruments, everyday objects and musical toys create choreographed actions and control the various extended cyberinstruments. The cyberinstruments expand the space for musical action while timbrally enhancing their physical counterparts, participating in the creation of hybrid analog-digital instruments and providing a resonant space for the performance given on the physical instrument. The extended cyberactions include qualitative augmentations of the extended cyberinstruments such as elongation of the cyberstring and deformation of the cyberbowl. The following table shows the compositions and the instrumentation involved in them.

Table 4. Compositions with extended cyberinstruments.

Title	Year compo-sed	Instrumentation	Cyberinstrument	Physical Modeling Approach	Implemented Environment and Designer
Garden of the Dragon	2003	Amplified cellophane, plastic corrugated tubes and electronics	Singing cybertube	1-d waveguide	MAX/MSP; S. Serafin
Three Movements	2004	Unprepared piano and electronics	Bowed cyberstring	1-d waveguide	MAX/MSP; S. Serafin
Revelations	2005	Circular toys, resonant plates and electronics	Bowed percussion cyberbar Cybershakers Bowed cyberstring	1-d banded waveguide PhiSEM 1-d	MAX/MSP-PerRColate; Georg Essl and Perry Cook; D. Trueman and L. Dubois impl. MAX/MSP-PerRColate; Perry Cook; D. Trueman and L. Dubois impl.

				waveguide friction model	MAX/MSP; S. Serafin
All Forgotten	2006	Piano and electronics	Cybermarimba	Modal synthesis	MAX/MSP; S. Serafin
Air	2006	Fujara and electronics	Cyberfujara	1-d waveguide	MAX/MSP; S. Serafin
To Where He Waited	2006	Cello and electronics	Cybermembrane	2-d waveguide mesh	MAX/MSP-PeRColate; Julius Smith and Gary Scavone; D. Trueman impl.
Concealed	2006	Flute and electronics	Cyberflute	1-d waveguide	MAX/MSP-PeRColate; Model by P. Cook; D. Trueman and L. Dubois impl.
In Secret	2006	Oboe and electronics	Singing cyberbowl	1-d banded waveguide	MAX/MSP; S. Serafin
En Una Noche Oscura	2007	Flute, violin, cello, piano and electronics	Singing cyberbowl	1-d banded waveguide	MAX/MSP; S. Serafin
Guiding Night	2007	Violin and electronics	Plucked cyberstring	Extended Karplus-Strong Algorithm	MAX/MSP; S. Serafin
Neither Stirred, Nor Shaken	2007	cocktail glasses, shakers, blenders and electronics	Bowed cocktail cyberglass Cybershakers	1-d banded waveguide PhiSEM Approach	MAX/MSP; S. Serafin MAX/MSP; P. Cook; S. Serafin impl.
Zvonenie	2007	4-channel electronics	Cyberbells	Mass-spring-damper	GENESIS; J. Kojs

3.1 Garden Of The Dragon (2003)[13]

Garden of the Dragon for amplified cellophane, plastic corrugated tubes, and electronics is a composition which engages a daily object

[13] Discussion of *Garden of the Dragon* is adapted from *Computer models and compositional applications of plastic corrugated tubes* (Serafin and Kojs 2005).

(cellophane) and a musical toy (plastic corrugated tube) in a musical dialogue with the computer. The purpose of this project was to compose a piece which can be performed by non-musically trained performers. Cellophane and tubes are fun and easy to perform with, and they can be located in any hardware/craft store.

The composition presents an ecosystem between two objects, whose sonic elements are typically unnoticed, a concept inspired by *Bugs*, a documentary 3D-movie released by Sky Films (2003) in which a small portion of the rain forest is visually amplified. The movie shows a magnified ecosystem with its inhabitants such as a variety of insect in all stages of their life. This type of ecosystem is normally unavailable to humans' eyes. In *Garden of the Dragon*, the performers' actions and stage movement amplify the physicality and potential for musical expression of these daily objects. The extended cybertube enables further augmentation of one of the instruments, this time beyond the scope of physical reality.

Three or more performers doubling the parts can perform the piece. The actions they perform include molding the cellophane with their hands, whirling the tubes, blowing inside the tubes, scraping them with their fingernails and tapping on them. The players' sonic output is analyzed in the computer and excites the cybertubes. Bursts of cellophane and the sonic input of the physical tubes excite the virtual tubes, the ones with dimensions non-existent in the physical world producing novel timbres in this piece.

Garden of the Dragon has a three-part arch form. The first section (0—ca. 3'20") presents percussive and noisy cellophane sounds. The cellophane players perform with the instrument placed on a microphone. The electronics of this part consist of pre-recorded and digitally processed cellophane samples. The section culminates at 2'56" when the players one by one release the cellophane and move away. The following figure shows the notation of music written with amplified cellophane.

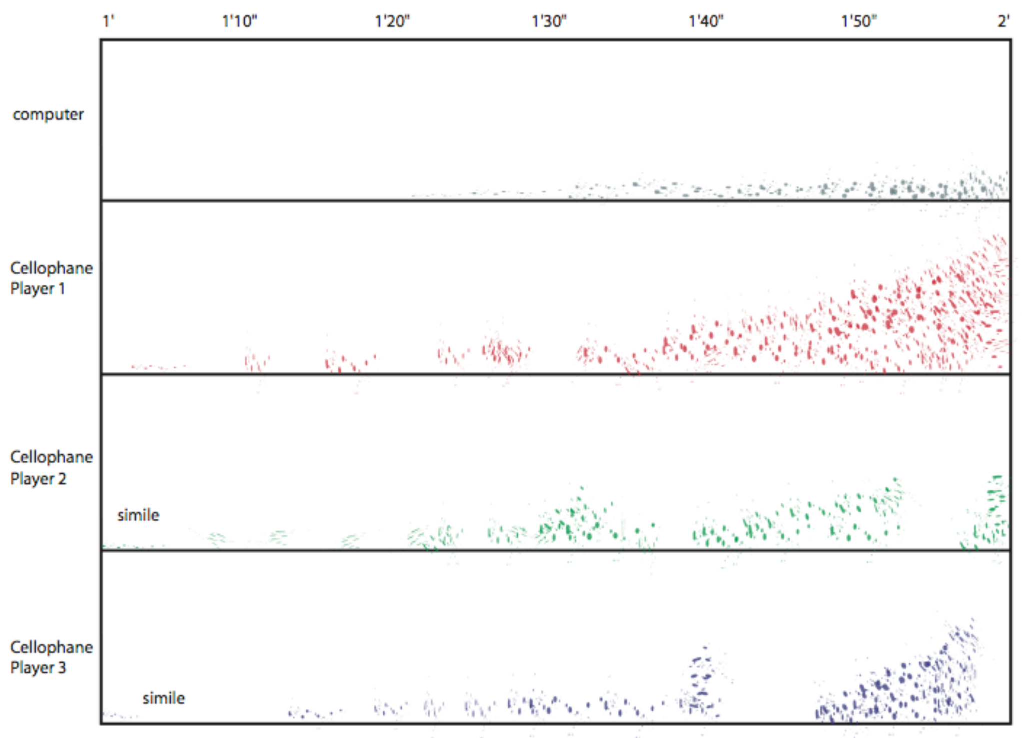

Figure 22. *Garden of the Dragon*, the score page 2. The horizontal axis indicates time. The vertical axis displays the density and amplitude of the gestures.

The second part (ca. 3'20"—7'20") introduces the tube sound. The sound of the cybertube emerges from the cellophane sound, which is achieved by the cellophane players inducing the cellophane sound samples into the cybrinstrument. A microphone tracks the cellophane signal and transfers it to MAX/MSP where its amplitude components act as the excitations for the cybertubes. Accumulation of sound breaks soon after the physical tube performs its highest reachable harmonic (7’10”). The performers stop whirling the tubes and get ready to blow inside and scratch the instrument. Figure 23 exemplifies the graphic gestures used to notate all performable harmonics.

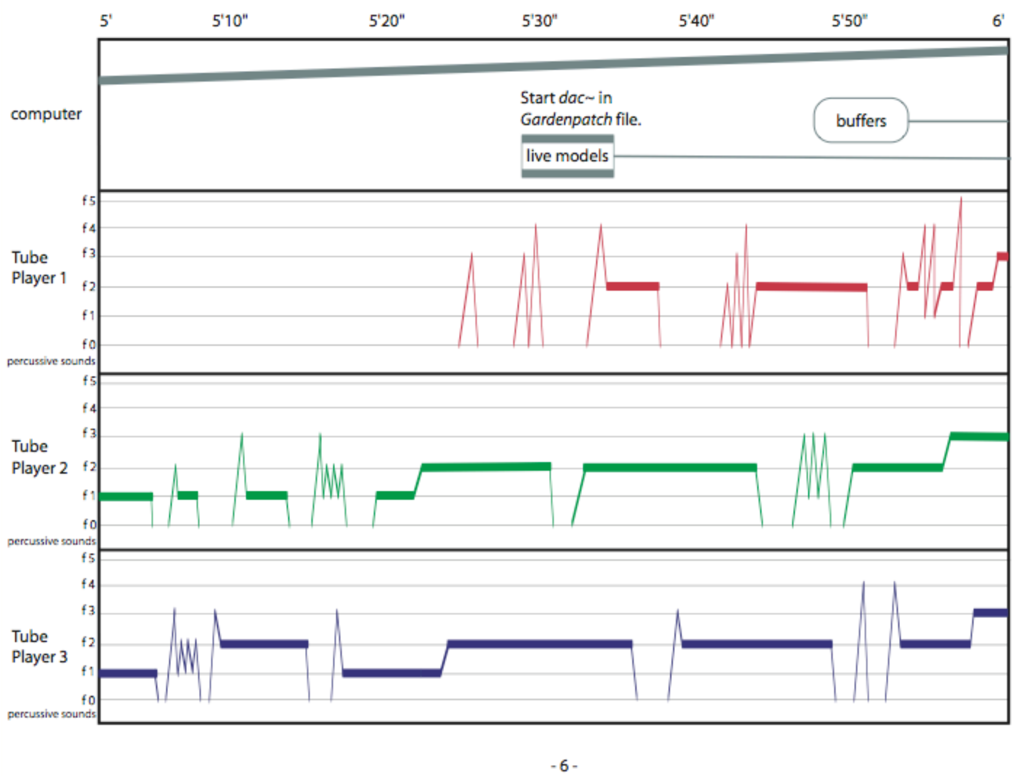

Figure 23. *Garden of the Dragon*, score page 6. The lines f0—f5 show all performable harmonics with f0 being the fundamental.

Noisy percussive sounds return in the final part (7’20”—9’) with newly introduced performing actions such as blowing inside the tube, scratching its surface and tapping on its ends. The slightly pitched sounds of the blown tubes dissolve into the non-pitched noises of tapped and scratched instruments in the end of the composition as indicated in the following figure.

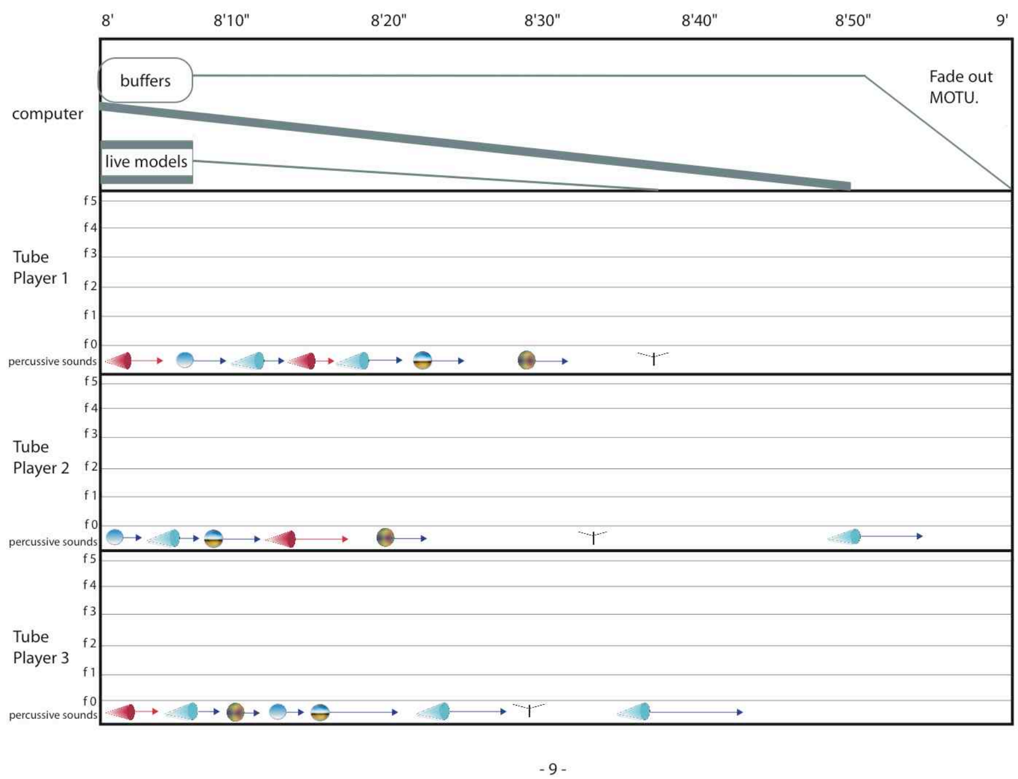

Figure 24. *Garden of the Dragon*, score page 9. The symbols indicate performing techniques such as a variety of blowing inside the tube (left oriented cones), tapping on it (the circles) and scratching it with nails (the fork).

The players' movement on the stage accentuates the composition's arch form. The performers travel from the central front stage to the back stage and again to the central front stage. A conductor or a big stopwatch indicate the time since the composition, as shown in the score examples, is notated in seconds. The following figure shows the performance trajectory.

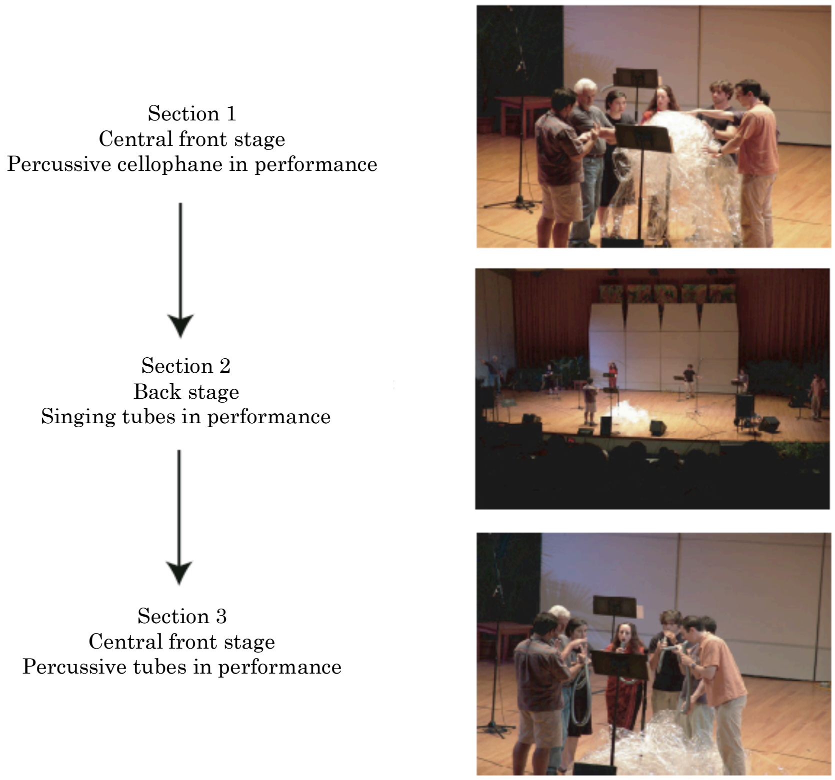

Figure 25. Garden of the Dragon. Performance Trajectory. The pictures by Rolf Nordahl from the performance at ICMC 2004, Miami, FL.

S. Serafin implemented the model of the singing tube as an external object in the MAX/MSP environment. The cybertube expanded the sonic limits of the physical instruments, namely parameters such as vibrato, Doppler effect, frequency and transitions between adjacent frequencies, amplitude and noise-to-pitch ratio. The cybertube enables control over all aspects of the tone production. The physical and virtual tube parameters are compared in table 5.

Table 5. Parameters of physical and virtual singing tubes.

Parameter	Physical tube	Virtual tube
Pitch	Fixed	Variable
Vibrato	Fixed	Variable
Transitions between pitches	None	Variable
Amplitude	Fixed	Variable
Noise-to-pitch ratio	Fixed	Variable

The vibrato of the physical tube is subtle and closely centered around its resonant frequency. The cybertube made possible continuously intensified and weakened vibrato variations. Vibrato alterations and Doppler effects are specifically observable in the pre-recorded part.

The MAX/MSP patch was set so that the cybertubes would respond to the amplitude and frequency modifications of their physical doubles. The *fiddle~* object tracks both the amplitudes and frequencies of the physical tubes. The number of sounding cybertubes is proportional to the amplitude of physically present tubes, a higher amplitude triggering a larger number of virtual tubes. The following example displays the amplitude control over five cyberinstruments.

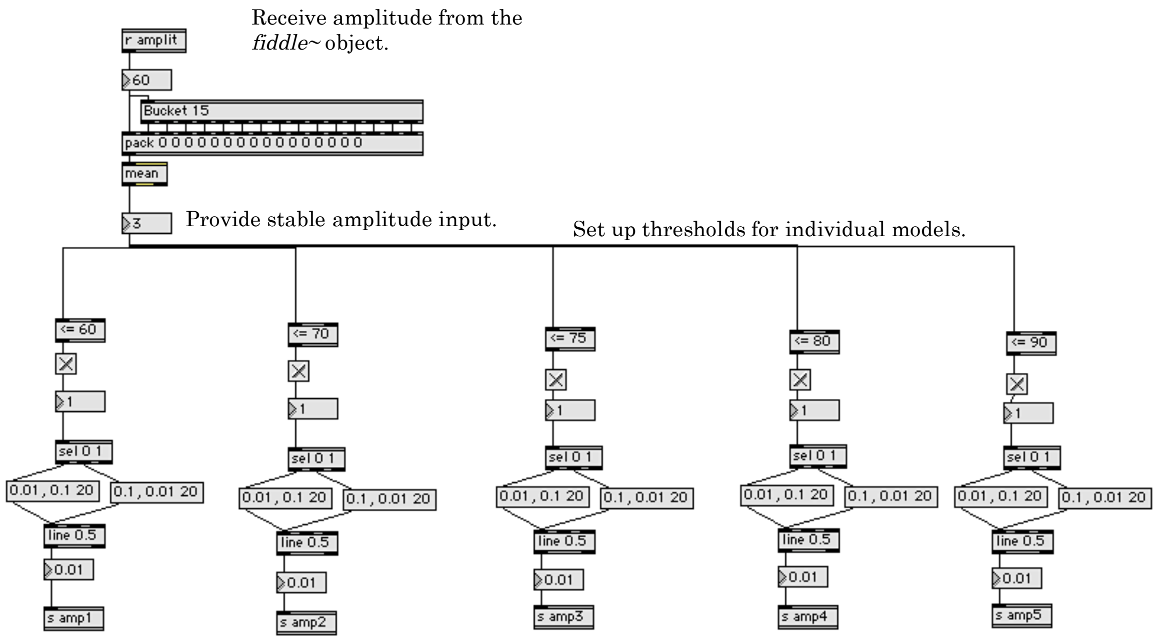

Figure 26. Relative amplitudes are split to five bands which control five cybertubes.

Additionally, specific amplitudes of the physical tube correspond with specific frequencies. The general observation is that the tones of higher frequency have higher amplitude and vice versa. The cybertube enabled the variation of the tone's amplitudes independently of their frequencies. Various transpositions of the physical tube pitches became the fundamental tones for the cyberinstruments. The following table compares the frequency spectra of the physical and cybertubes used in *Garden of the Dragon*.

Table 6. Fundamental frequencies and harmonics of physical and virtual tubes.

Instrument/ Frequency (Hz)	F1 The fundamental	F2	F3	F4	F5	F6
Physical tube	156	**310**	**464**	**625**	**768**	**925**
Cybertube 1	38	**73**	**110**	**147**	**185**	**220**
Cybertube 2	82	165	**247**	**330**	**415**	**494**
Cybertube 3	139	277	415	**554**	**698**	**831**
Cybertube 4	175	349	523	698	**880**	**1047**
Cybertube 5	311	622	932	1245	1568	**1865**

Real-time cybertube tones present particular intervallic transpositions of the physical tube pitches. Cybertubes 1 to 5 were transposed in semitones as 25, -11, -2, +2, +12, respectively. Such transpositions suggest registral extensions of the instruments which are impossible in physical reality. The virtual tube further extends the fixed leaping to and from neighboring tones of the physical tube with fluid transitions using glissando and microtonal motion. While the tones of the physical instrument are based on a harmonic series, the cybertube can generate a tone series founded on any relationship.

The noise coloration of the tone is restricted in a physical tube, but in a cyberinstrument this may be adjusted. For example, when the real-time cybertubes first appear in the composition, they emerge from the cellophane percussive noises prevailing over the pitch. As the composition progresses the pitch is more clearly articulated. The following figure displays the cybertube interface in MAX/MSP as used in *Garden of Dragon*.

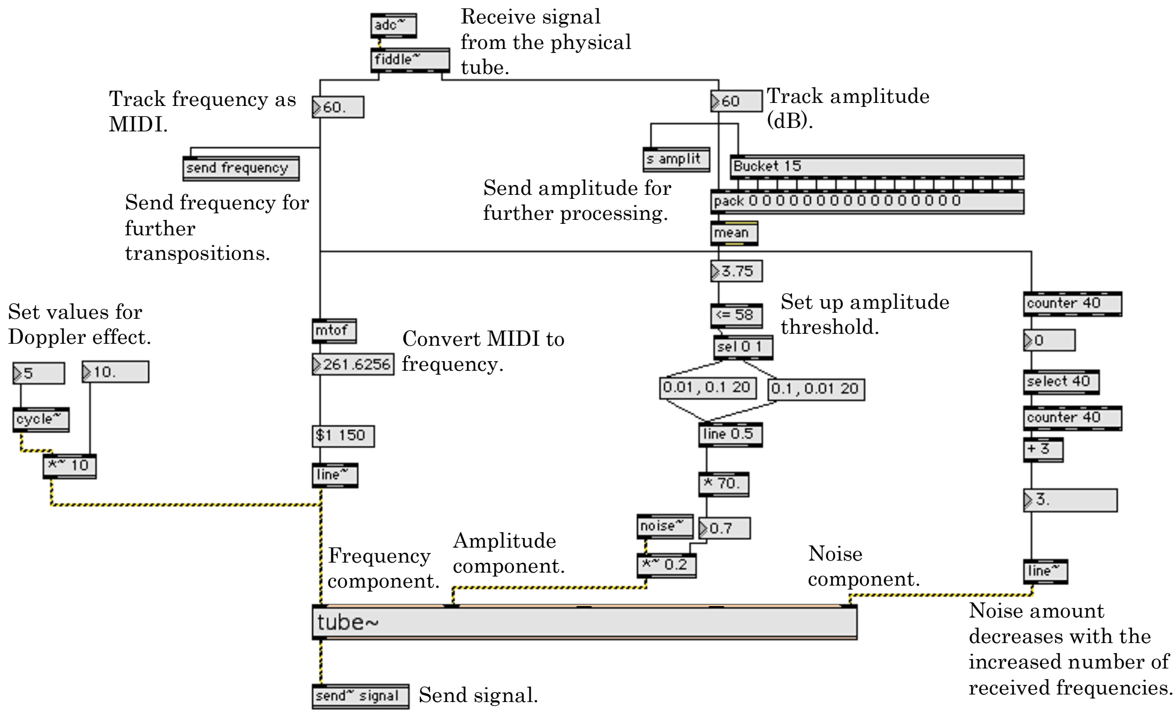

Figure 27. S. Serafin's MAX/MSP implementation of the cybertube as used in *Garden of the Dragon*.

In addition to the real-time tube performance, short excerpts of the physical tube sounds are recorded, transposed, delayed and looped in the MAX/MSP patch. The density of texture and sound's amplitude increase as the piece reaches its major climactic moment at 7'10" as shown in the following figure. The figure also summarizes the progressions of individual musical parameters. The arch form, as seen through the noise-to-pitch-to-noise trajectory, is most noticeable in the physical tube's part.

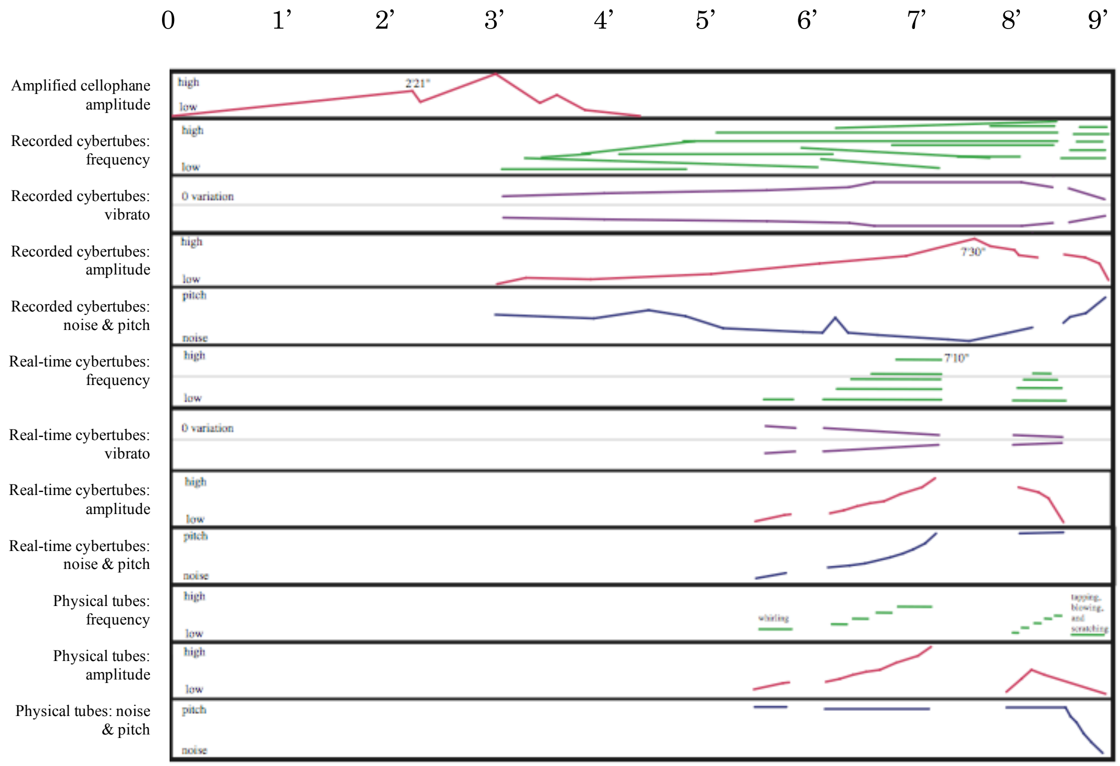

Figure 28. The performance involves cellophane, physical tubes and ten pre-recorded and five real-time cybertubes.

3.2 Three Movements (2004)[14]

Three Movements is a composition for *unprepared* piano and electronics. The composition explores technique for creating new instruments, defining the instrument's components, such as the case, strings and keyboard mechanism, as independent acoustic separation-derived musical

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[14] I first discussed the following materials in *Piano case, keyboard, and strings: Separation-derived musical instruments in an interactive composition* (Kojs 2005).

instruments.[15] The piece also investigates the expressive properties of the friction bowed cyberstring as modeled in (Serafin 2004), exciting the string with the acoustic piano while highlighting the acoustics of its own sound production.

The piano case, keyboard and strings are employed with varying predominance in the different movements. Actions applied to the resonating piano body enliven *Palms on the Strings.* Sliding and playing actions on the keys which do not produce any concrete pitch results in a set of percussive sonorities positioned on the threshold of hearing in *Sliding Quietly*. A conventional performance in regular mode over a silent keyboard is the primary action in *Bowed Fingertips*.

A friction driven cyberstring also functions as a virtual separation-derived musical cyberinstrument. The separation-derivation technique for creating new musical instruments is based on the simple proposition that an instrument consists of at least two components: an exciter and a resonator. Once we separate the components of a complex acoustic instrument, these become instruments themselves. In the case of the piano, the frame, plate and soundboard, strings, keyboard mechanism and pedals all become such instruments.

The acoustics of the piano are described in *The physics of musical instruments* (Fletcher and Rossing 1998). It identifies three primary agents

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[15] The author used other separation-derived acoustic musical instruments such as piano lid and piano pedal in *Dynamisms* for piano and orchestra (2001).

involved in piano sound production: the striking mechanism (keyboard and hammers); the string; and the piano case with soundboard, frame and plate as shown in the following figure.

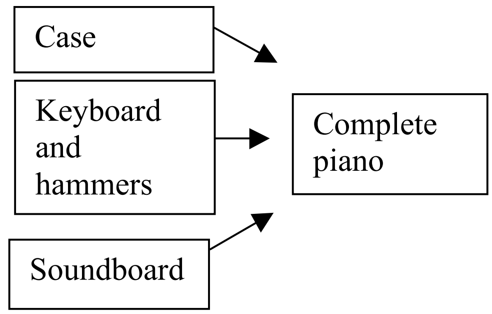

Figure 29. Synthesis diagram for piano sound production.

The keyboard and hammers are the exciters. The strings and case function as the resonators. These individual components are detailed in *Quality of piano tones* (Fletcher et al. 1961), *Five lectures on the acoustics of piano* (Askenfelt 1990), *Design and tone in the mechanoacoustic piano. Part 1* (Conklin 1996a) and *Design and tone in the mechanoacoustic piano. Part 2* (Conklin 1996b). In *Three Movements*, three analyzed components are conceived as individual instruments as displayed in figure 30.

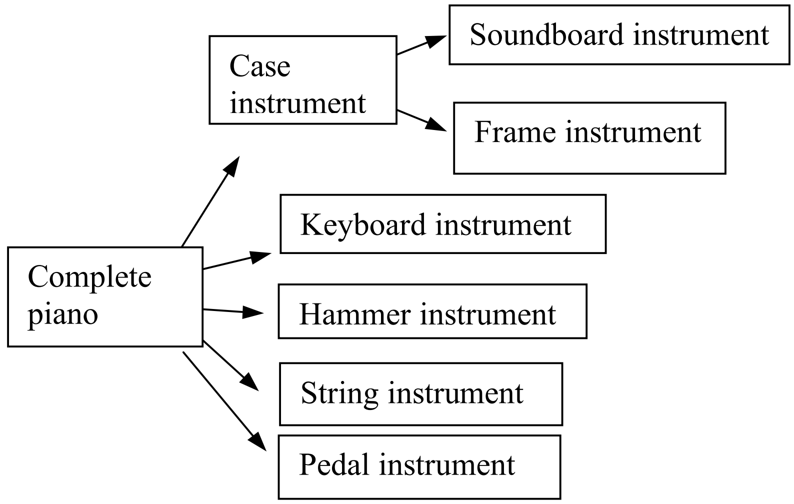

Figure 30. Piano separation-derived instruments.

A single complex instrument can therefore parent a variety of separation-derived instruments. These instruments naturally retain certain physical and, thus, sonic characteristics of their parent, but new attractive sonorities emerge when the characteristic qualities of a separation-derived instrument are developed and enhanced. In *Three Movements*, the case instrument is considered one instrument. (Pedal and hammer instruments, however, are not used.)

3.2.1 *Palms on the Strings*

In the opening movement~~,~~ the piano case is defined as a percussion instrument. The performer uses its frame, soundboard, metal dividers and strings in a variety of performance actions such as dynamically varied rubbing, tapping and hitting with the palms and fingers. Keeping the sustain pedal down throughout the movement allows the slightest excitation to enliven the case.

The most satisfying sonorities occur at these miniscule excitations, and a microphone is positioned inside the case to amplify the sounds and transfer them to MAX/MSP, where an artificial resonator is created out of a bank of delays. Adding this resonating quality completes the case as a stand-alone instrument.

The case also functions as a controller. When the metal dividers are stuck, the signal is processed by a series of comb filters. This results in a sound resembling a pulsating didgeridoo. This establishes a clear sense of the case being the excitation mechanism resonating in virtual computer space.

The cyberstring generates a supplemental timbre layer in the first movement. *Palms on the Strings* employs a number of pre-recorded and pre-processed friction cyberstrings. Functionally, the string is employed to generate a background tapestry for the evolving sonorities of the piano performed inside, with the cyberstring evidently playing a more active role in the second and third movements.

The following figure displays a portion of the score. The horizontal bracket frames the system of two staves incorporating both electronics (top) and piano (bottom). The vertical orientation of the system represents time measured in seconds. The horizontal orientation of the computer music part indicates amplitude fluctuation (centered around invisible line 0 in the middle of the system). The top system represents transformations in computer-processed sounds as follows: pre-recorded string models (dense red wave form), sampled piano (green line) and rhythmic cues (pink pattern and line).

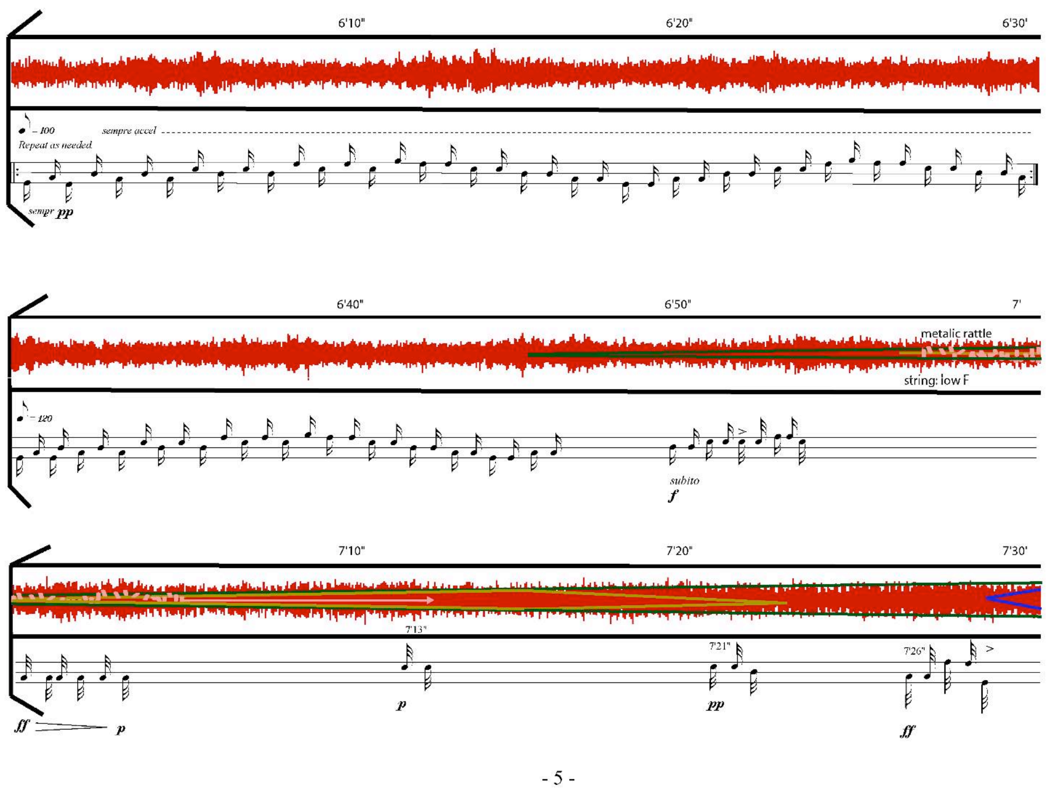

Figure 31. The piano part is scored in three lines and three spaces. These represent performance regions inside the case: three metal dividers (spaces) and strings areas positioned between them (lines).

2.2.2 *Sliding Quietly*

In this movement the keyboard is characterized as a separation-derived acoustic instrument. The performer slides his/her nails, knuckles and palms on top of the keys without fully depressing them. Since the hammers never strike the string they do not produce a pitch properly speaking, but instead an array of slightly-pitched percussive sonorities. A range of these sonically original nuances forms the expressive range of the instrument. The frequency of the sound is proportional to the velocity of the performed glissando gesture.

The hand-sliding actions also function as an excitation mechanism for virtual bowing. Two microphones positioned over each end of the keyboard sonorities transmit the signal to MAX/MSP, where the signal is amplified and analyzed to excite the bowed cyberstring. This results in a simulation of either *saltando* or plucked string sonorities. The frequency spectrum of the model is pre-assigned and corresponds to the overall pitch design of the composition.

Figure 32 exemplifies an instant in which the plucked string (the purple wave form in the center), piano samplers (green line), friction string (the yellow line) and piano performance (the bottom system) align to compose the score. The straight lines connecting the initial and ending points of the gesture represent gliding actions.

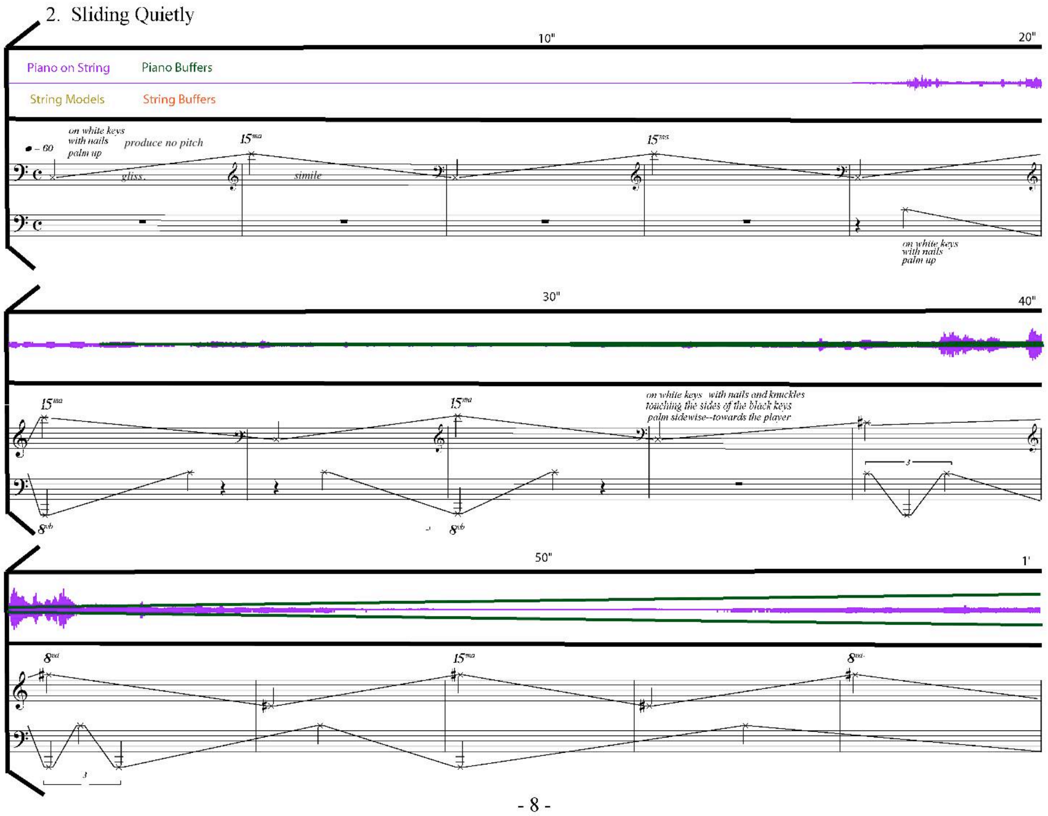

Figure 32. A score excerpt from Sliding Quietly. The traditional notation is used to suggest actions such as gliding on the silent keyboard.

3.2.3 *Bowed Fingertips*

For the most part, the pianist performs in normal mode without depressing the keys in *Bowed Fingertips*, while the cyberinstrument functioning as a resonant space for the keyboard performance. In the opening section, the pianist's percussive impulses excite the cyberstring similarly as in the second movement. Later in the movement, however, the pianist depresses the keys fully and produces pitches. These are analyzed in

MAX/MSP and provide the real-time input for a set of cyberstrings, and the amplitudes of the piano strings control the changes in pressure and the velocity of the virtual ones. The frequencies of the piano string are transposed to the extremities before they are induced to the cyberstrings so that the cyberinstruments produce pitches normally unavailable on the piano. The spectra of multiple virtual strings are further reinserted in a cyberstring network.

In this process, the cyberstring network gains a certain independence from the piano performance and produces indeterminate novel sonorities, and this is here proposed as a virtual separation-derived musical instrument. This cyberstring is a combination of three digital waveguides connected in parallel and excited by a friction mechanism. (The friction interaction is a described in Serafin's *The sound of friction: Real-time models, playability and musical applications*, 2004.) Serafin implemented the instrument in MAX/MSP as an external object *squeaking~* with the following inputs: frequency elements, bow force, bow velocity, bow position and residual component.

This cyberinstrument may be controlled externally or internally. In the case of external control, the pianist performs on the keys in normal mode without producing any pitch. The string responds to the impulses provided by the piano in the same way as in the second movement. Later in the movement the model develops into an autonomously driven cyberinstrument, created by analyzing one model's output and cross-synthesizing it with another replica of itself so that the model functions both as an exciter and resonator. Some input parameters are still provided, but the sonic separation of the model from the keyboard's input is transparent. The cross synthesis feedback loop develops in the second part of the movement.[16] Figure 33 shows the cyberstring as it is used in *Bowed Fingertips*.

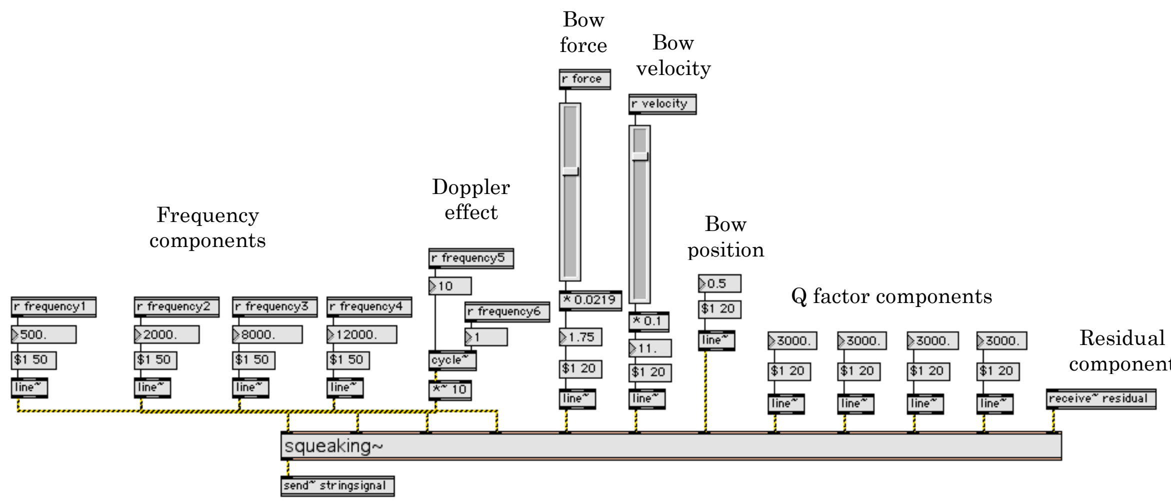

Figure 33. S. Serafin's cyber string implemented in MAX/MSP as the *squeaking~* external object.

The piano produces a small number of tones later in the movement. These pitches, their durations and the distance between them and between their repetitions are systematically arranged. The multidirectional rotation of pitches B, A, C and B flat constitutes the skeleton for the vertical and horizontal design of the piano and model. The silent key piano performance

[16] Note that regardless of the adventurous combination this is still a case of an extended and not hybrid cyberinstrument. It is the signals and not the instrumental parts that are combined.

mode returns towards the end of the movement, as shown in the following score example.

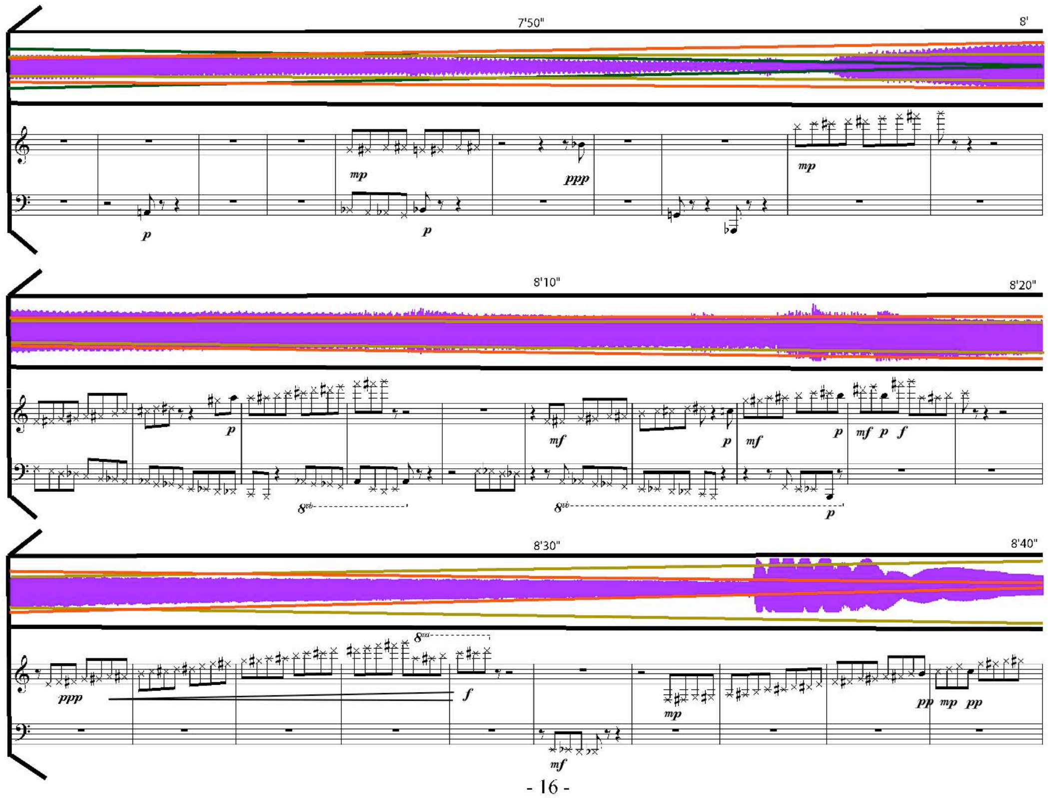

Figure 34. The emergence of pitched piano material is indicated in the filled note heads. The top system shows the signal of piano driven bowed cyberstring (dense centered purple form), autonomously driven friction cyberstrings and string samplers (red line). The bottom system displays the piano part. The cross note heads indicate non-depressed key performance, while the filled ones require full key depression.

Three Movements demonstrates the separation-derivation technique for creating new musical instruments. The new instruments originate as individual components of complex musical instruments. The piano case, keyboard and string were characterized as such instruments and excited by a variety of physical actions (including plucking and bowing). The cyberstrings extended the timbral characteristics of the separated instruments.

3.3 Revelations (2005)[17]

Revelations for circular toys, resonant plates and electronics primarily explores the sonorities of physical toys and cyberpercussion. It uses plastic superballs, glass marbles and metal Bocci (Patang) balls to control virtual maracas, guiro and bamboo chimes. Physical actions such as bouncing, rolling and scraping the circular toys against the resonant plates made of Plexiglas, glossy and matte plastic, aluminum and brass excite the unrealistically shaped cybershakers such as maraca, cabasa and guiro (Cook 1997, Cook 2002). The external MAX/MSP object *bonk~* (Puckette and Apel 2003) then tracks and analyzes the amplitude of the performance audio signal. The bowed percussion cyberbar (Essl and Cook 2000) and friction bowed cyberstring (Serafin 2004) are also employed to complement the scraping actions of a physical rubber ball against hard surfaces.

In general, the cyberinstruments contribute to the timbral and temporal extension of the quickly decaying scraping gestures of the physical plates, particularly the plastic ones. Hybrid analog-digital resonating

[17] *Everyday objects in interactive electroacoustic compositions* (Kojs and Serafin 2007b) describes the composition in detail.

structures resulted from the combination of physical scraping excitation and reverberation of virtual instruments.

The piece is divided into four parts according to the prevalence of particular actions: shaking, scraping, rolling and bouncing. The physical performance modes do not necessary align with the computer-simulated actions, the acoustic bouncing, for instance, complements the physically modeled shakers in the opening section. A microphone is placed under each plate as shown in figure 35 to transfer the audio signal into MAX/MSP.

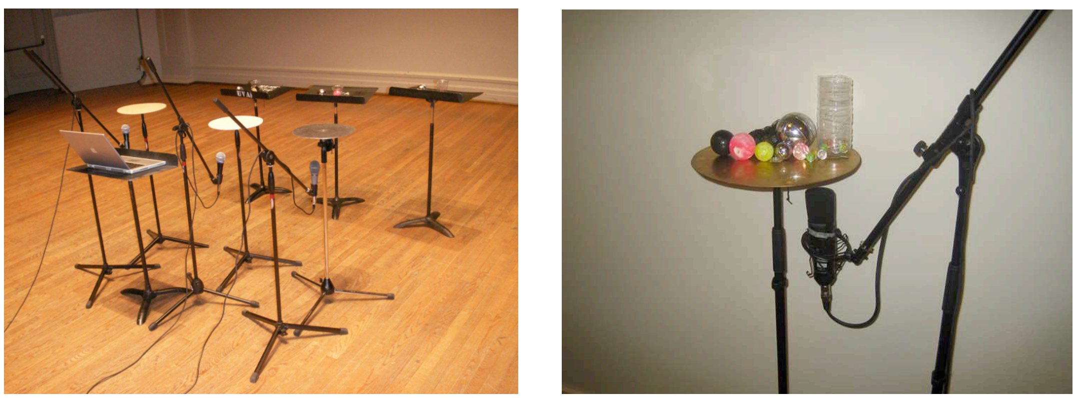

Figure 35. Circular toys and a metal resonant plate set up in *Revelations*.

Here the recognition of amplitude gestures is of primary interest. Mapping between the physical and cyberinstruments is based on amplitude expressiveness. Considering the predominantly percussive nature of the sounds produced by circular toys, amplitude gestures assist in recognizing and tracking performance modes such as bouncing (identifiable by short discontinuous bursts of energy in amplitude spectrum), scraping (decaying amplitude gestures of short duration and initial strong attack), rolling (continuously sustained amplitude with slight fluctuations) and shaking (continuously sustained amplitude with larger peaks). The following score example shows the relationship between the computer-generated and performance actions.

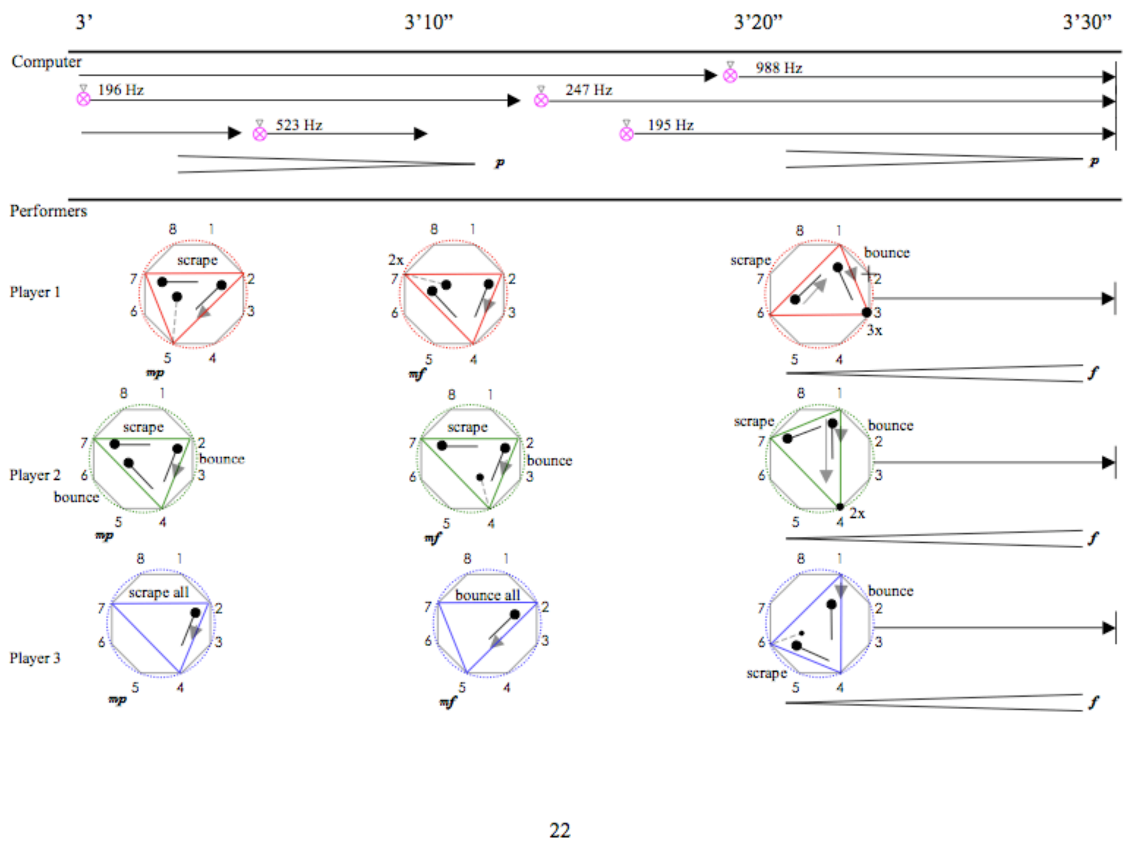

Figure 36. Each plate is divided into eight spatial sections which are also eight temporal units. Scraping and bouncing actions begin at places and times as indicated by the corners of the triangles thus creating a variety of 3-beat rhythms.

While cybershakers simulate shaking and a bowed percussion cyberbar enables rubbing, gestural models of rolling and bouncing created in MAX/MSP simulate such actions in cyberspace. Three performers operate a set of circular toys to excite resonant plates and cyberinstruments. The cyberinstruments enrich the timbral tableaux of the physical instruments in *Revelations*.

3.4 Air (2006)[18]

The composition *Air* involves a fujara, an ethnic pipe instrument, in an interactive performance. The composition presents a dialogue between physical and cyberfujaras, recontextualizing an ancient musical instrument in our era.

The fujara is an indigenous Slovakian folk instrument originating in the Great Moravian Empire in the tenth century (Macak 1995). The fujara is a wooden pipe made of semi-hard wood from indigenous trees, 165—190 cm long and 3—5 cm wide. The traditional Slovak fujara has three holes, though fujaras with more holes (as many as 9) may be found in some Slovakian regions. A traditional three-hole fujara is displayed in figure 37.

[18] *Air* was first described in *The fujara: A physical model of the bass pipe instrument in an interactive composition* (Kojs and Serafin 2006).

Physical dimensions of a fujara.
1. length of resonator,
2. inner diameter of the instrument
3. total length
4. tone-hole diameter
5. distance between the tone-holes
6. distance between the bottom end of the fujara and the first tone-hole.

Adapted from (Filo 2004).

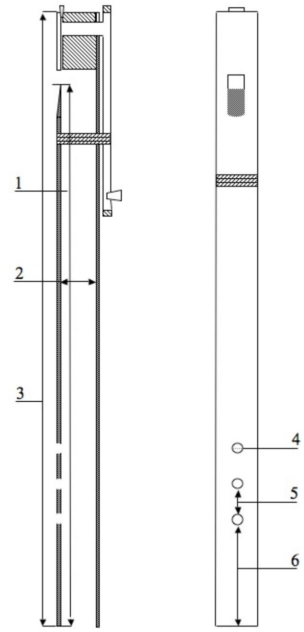

Figure 37. Traditional Slovakian three-hole fujara in G and its physical dimensions.

Initially, the shepherds played the fujara to express solitude and the pastoralism in their quotidian life in the mountains. Solo folk songs performed on the fujara were often sustained and melancholic in nature. Over the centuries, it became common for groups of three to seven players to performing music of a variety of moods and tempi using these instruments. To these days, the fujara thrives in the Southwestern region of Detva and elsewhere.

The fujara's tone is produced by blowing into the small mouthpiece, attached to the shorter tube. The tone consists of overtones based on harmonic series. Overblowing technique produces individual harmonics, with higher air pressure producing a higher harmonic. As with the other open ended tubes in which the fundamental frequency does not sound, the first resonating tone on the fujara is the first harmonic (the octave). The user produces individual tones by increasing or reducing air pressure and adjusting the position of the toneholes (covered, open or combined).

The spacing of the three toneholes insures that the covering and opening of them in sequence will produce the initial major tetrachord. A simultaneous variation of air-pressure and fingering facilitates upward and downward stepwise motion. While constantly increasing the air pressure and changing the fingering properly, the performer can play an ascending major scale in the first octave and the mixolydian scale in the second octave on the traditional fujara. The fingering and resulting tones are shown in figure 38. The newer tuning method developed by Tomas Kovac suggests the correction of the second octave to the major scale.

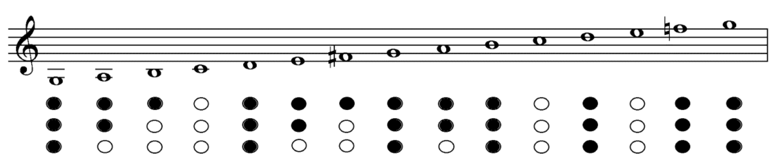

Figure 38. Fingering and possible tones on G fujara. Adapted from *Fujary, pistalky. (Fujaras and whistles)* (Filo 2004).

S. Serafin designed a cyberfujara using digital waveguide synthesis (Smith 2006), which is most efficient for the digital simulation of flute-like instruments (Kojs and Serafin, 2006). Both the main resonator and the shorter side pipe are simulated in it as one-dimensional waveguides. Visco-thermal losses are modeled as low-pass filters, and tone holes are modeled as proposed in (Scavone and Smith 1997).

Serafin implemented the model in a MAX/MSP environment for real-time operation as an external object *fujara~.* The fundamental frequency of cyberfujara controls the waveguide's length. Other control parameters are jet delay, noise and air pressure, and high-speed injections of air simulate the characteristic resonance of the fujara's overblowing technique.

The physical fujara functions as a controller for six cyberfujaras in real-time. A microphone positioned close to the opening of the instrument transmits the audio signal to Max/MSP, where its pitch and amplitude are tracked by the *fiddle~* object (Puckette and Apel 1998). The object works efficiently as the tracked tones show stable fundamental frequencies and amplitudes. In addition to the fundamental frequency, up to three higher sinusoidal components are extracted from the tone's spectrum. These are rescaled and mapped as the fundamental frequencies of the cyberfujaras.

The virtual fujaras extend the frequency range, amplitude envelope contour and duration and timbre of the physical instruments. The cyberinstrument further facilitates circular breathing, an effect that is impossible to achieve with the physical fujara. In addition to the real-time sounds of the physical and physically modeled fujara, the textures of *Air* present pre-processed sonorities of the physical instrument.

Air is structured in three sections. The pitch material of each section is derived from a Slovak folk song. Timbrally, the composition follows the trajectory from the idiomatic sound of the physical fujara to the sounds produced by extended performance techniques, and, finally, to the sonorities of the cyberfujara.

3.5 Dark Night Series

The following eight compositions belong to a series of works based on individual verses from St. John of Cross's poem *Noche Oscura* (*Dark Night)*. Most of the compositions combine instrumental sonorities that lie on the border of hearing with augmented sonorities of various cyberinstruments created via physical modeling synthesis. Table 7 lists the pieces, their instrumentations and cyberinstruments if used.

Table 7. *Dark Night* series of compositions.

Verse from St. John's *Dark Night*	**Title and year composed**	**Instrumentation**	**Cyberinstrument and modeling technique (if used)**
1	*En Una Noche Oscura (2006)*	Flute, violin, cello, piano and electronics	Tibetan cyberbowl (1-d waveguide)
2	*Concealed (2006)*	Flute and electronics	Cyberflute (1-d waveguide)
3	*In Secret (2006)*	Oboe and electronics	Tibetan cyberbowl (1-d waveguide)
4	*To Where He Waited (2006)*	Cello and electronics	Cybermembrane (2-d mesh waveguide)
5	*Guiding Night*	Violin and electronics	Plucked cyberstring (Karplus-Strong algorithm)
6	*There He Stayed (2007)*	Everyday objects and voices	
7	*And All My Senses Suspended (2007)*	Flute, electric guitar, double bass and piano	
8	*All Forgotten (2006)*	Piano and electronics	Cybermarimba (Modal synthesis)

The pitch material of the series is directly derived from the Spanish poem as a transcription of alphabet letters to musical tones. The letter H is rendered as tone B, and the letter B is rendered as the pitch of B flat. The combination “es” is translated as E flat and “as” as A flat.

The *Dark Night* compositions can be described as action-based music, as physical action is the primary means for musical expression. I developed this language of graphic symbols to embed actions in the score itself. For example, a circle in the score of *To Where He Waited* for cello and electronics will result in circular bowing.

3.5.1 En Una Noche Oscura (2006)

1. En una noche
oscura, con ansias, en
amores inflamada, ¡oh
dichosa ventura!, salí sin
ser notada estando ya mi casa sosegada.

San Juan de la Cruz: *Noche Oscura*.
Public domain.

1. On a dark night,
kindled in love with yearnings—oh,
happy chance!—
I went forth without being observed, my
house being now at rest.

Transl. E Allison Peers.
Public domain.

The composition *En Una Noche Oscura* for flute, violin, cello, piano and electronics explores numerous performative actions in meticulous detail. Control over each aspect of sound production on the instruments is displayed in the score, which is a choreography of movements to be performed on a particular instrument as shown in figure 39.

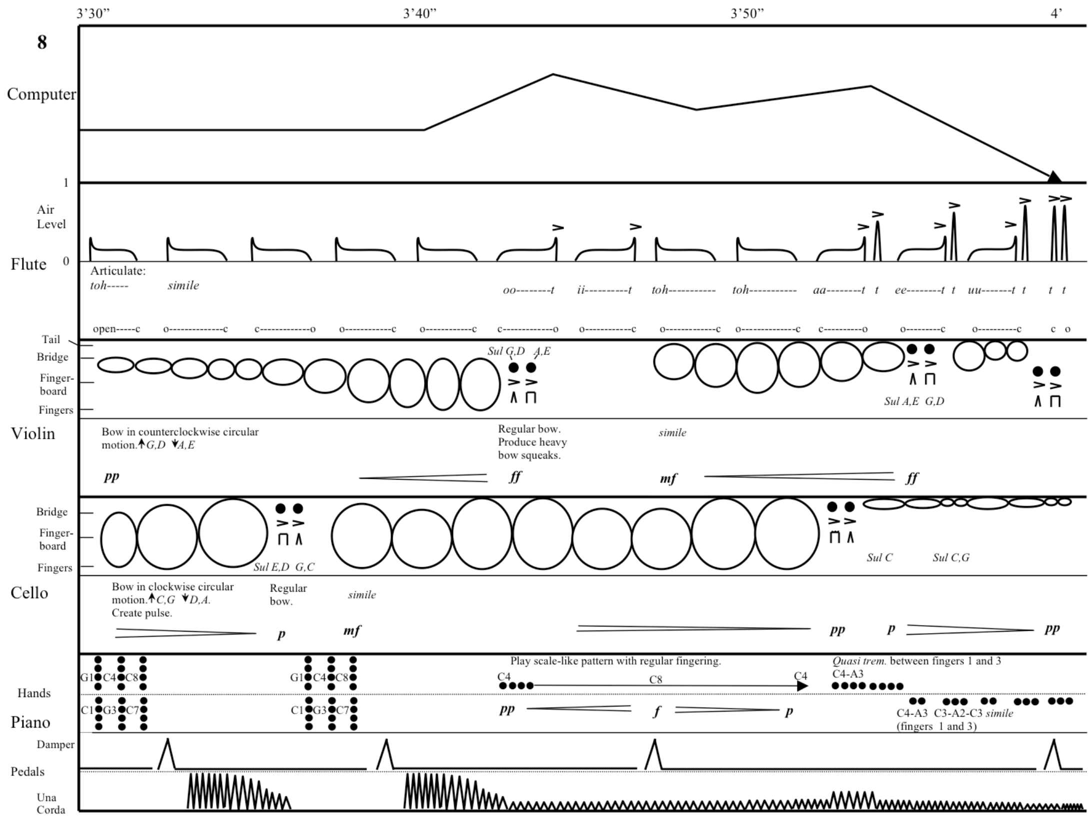

Figure 39. An example from the score of *En Una Noche Oscura*.

I extracted alphabet letters which match musical tones from the first verse and used this as underlying pitch material for the composition. Although heard only faintly, the exact letter-pitch sequence is presented in the flute part and mirrored in the rest of the ensemble. Even the piano, which plays on the closed keyboard and pedals only, performs gestures over the pitch areas which correspond to the given material. Once these are completed, the flutist (actually playing the lead role in the performance) annunciates the entire verse through the instrument, its gestures mirrored, inverted and developed by the rest of the ensemble.

In addition to the acoustic instruments, *En Una Noche Oscura* involves a Tibetan cyberbowl. Each physical instrument is miked and its signal energizes a different parameter of the same cyberbowl in MAX/MSP so that the ensemble of instruments collectively deforms the shape and size of the bowl. Mapping multiple instruments to a single virtual bowl generates parametrical situations non-existent in physical reality. The mapping assignment of a particular instrument to a particular cyberbowl parameter changes over continuously over time. Thus, the physical instruments and cyberbowl construct a network analog-digital instrument. The audio signal from the instruments is also fed into the bowl itself, which serves as a resonant filter and thus creates a virtual performance space for the performance, allowing eight-channel spatialization. I further designed a rotation algorithm to incite a contrapuntal relationship between the parametrical mapping and spatial distribution.

The cyberbowl is then parametrically deformed in real-time in this piece. Tapping and rubbing are the two primary cyberactions engaged in the excitation of the cyberinstrument. The virtual space of the bowl is further occupied by the audio signal from the instruments, and its identity is continuously extended with the external parametrical control. We rarely hear the characteristic singing bowl sonorities. The piece dissolves into silence as the musical gestures elongate at disappearing dynamics.

3.5.2 Concealed (2006)

2. A oscuras y segura, por
la secreta escala,
disfrazada, ¡oh
dichosa ventura!, a oscuras y
en celada, estando ya mi casa sosegada.

Juan de la Cruz: *Noche Oscura*.
Public domain.

2. In darkness and secure, by
the secret ladder,
disguised—oh,
happy chance!— in darkness and
in concealment, my house being now at rest.

Transl. E Allison Peers.
Public domain.

Concealed for flute and electronics is based on the second verse of the *Dark Night* and explores flute sonorities that lie on the border of hearing. *Concealed* investigates control over the flute performance actions which often result in colored noise. The cyberflute complements the instrumental noise with a generous supply of clear frequencies which further augment flute's registral and textural areas. Strict control over the physical and virtual sound productions enables the creation of a unique augmented analog-digital reality.

The composition is formally divided into three parts, the opening (0—1'50"), main body (1'50"—5'10") and closure (5'10"—7'10"). While the opening section explores the breathing patterns the main body of the composition investigates the use of text interwoven in a multitude of flute techniques. The words are initially presented in their original order. As the composition progresses, the text of the poem is continually fragmented. The disappearance of the voiced poem into the whistle tones, which signify the pitch-colored breathing, signalizes the closure. The electronic sounds of processed percussive key clicking then dominate the final portion of this section.

Performative actions on the flute are mirrored in the score. In order to achieve tight control over the sound production, the notation is split into four staves displaying pitch, dynamic envelope, breathing pattern and the openness of the blow hole as shown in figure 40. Additionally, it specifies performer's mouth shape as the performer often whispers the words in the instrument in addition to performing the music gestures. The score of *Concealed* combines traditional and graphic notations.

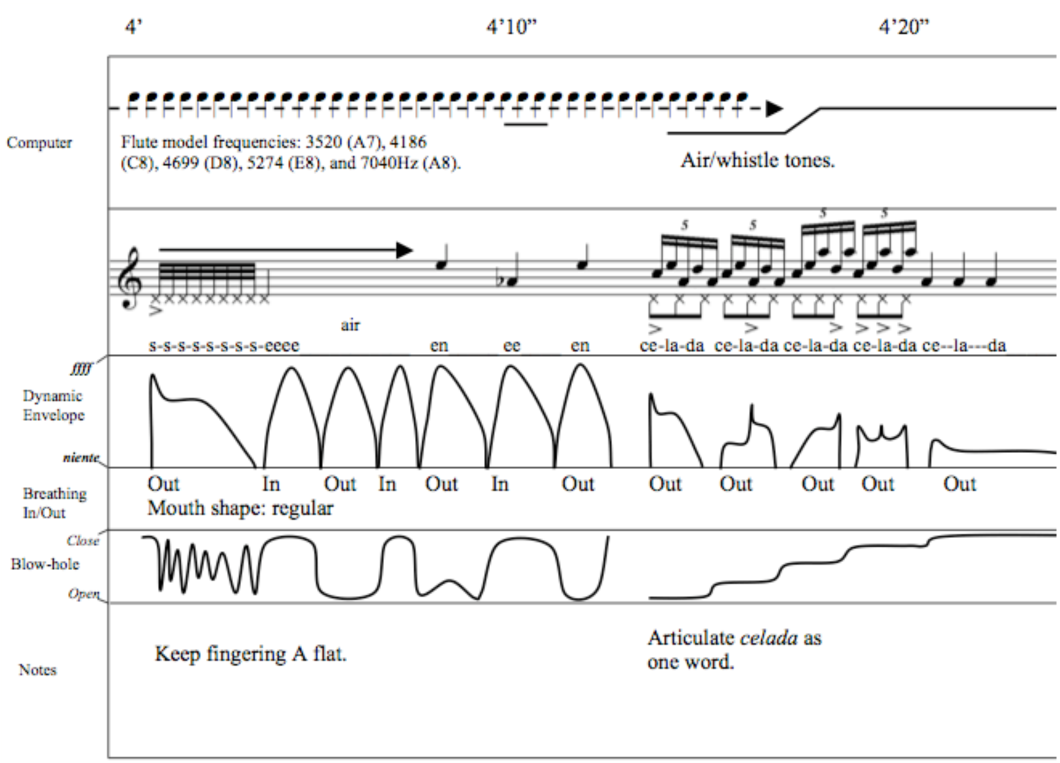

Figure 40. An example from the score of *Concealed*.

The acoustic flute is complemented and extended by the sonorities of the cyberflute. As the acoustic flute produces mostly noisy sonorities, it is the primary function of the electronics to supply the frequency components of the sounds. Structurally the electronics function~~s~~ as a background agent, an active participant and a soloist in *Concealed*. In the opening section the electronics contribute to the generation of the musical flow, which resolves at 1'40". In the main body of the composition the electronics' presence fluctuates. The electronics assist~~s~~ in creating a textural tapestry. Further the electronic sounds complement and respond to the instrumental part and gain a certain independence from it. In the closing, the computer sounds prevail as they resolve the dynamic acceleration of the final segment.

The electronics participation in the composition includes both pre-recorded music and real-time performance portions. The pre-recorded portion presents a combination of pre-processed flute sonorities and the sound of the cyberflute. The computer staff in the score shows flute's gestures and resonant frequencies.[19]

The signal of the flute performer functions as a controller for the cyberflute in real-time. The microphone tracks the signal and sends it to MAX/MSP, where it is simultaneously amplified, processed and fed into the

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[19] The real-time portion involves the MAX/MSP implementation of the flute physical model designed by Perry Cook (Cook 1992), who with Gary Scavone originally implemented the flute model in STK application (Cook and Scavone 1999). Dan Trueman later ported the model to MAX/MSP as an external object *flute~*, a member of the PeRcolate library of external object for MAX/MSP (Trueman and DuBois 2005).

cyberinstrument. Blending the sonorities of physical and virtual instruments results in the creation of a unique analog-digital instrument.

The cyberflute is characterized by a set of parameters such as breath pressure, jet angle, noise, vibrato frequency, vibrato gain and tone frequency as in figure 41, and augments the sonorities of the physical flute through the extension of its registral and textural shown arenas. While the cyberflute's frequencies also imitate the pitches of the letters from the poem, these are registrally spread beyond the range limitations of any physical flute, enabling it to produce tones such as G2 (98Hz) and E9 (10548Hz).

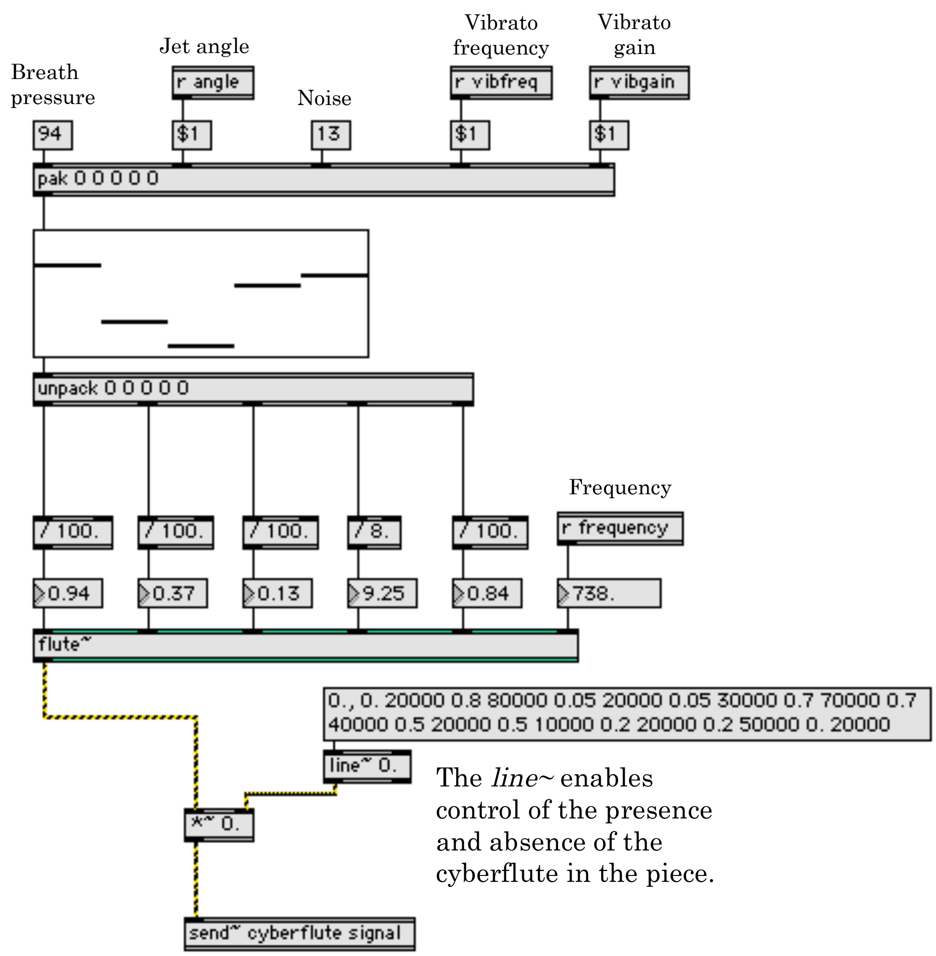

Figure 41. Cyberflute control interface in MAX/MSP.

The registers develop in the course of the composition in an arch shape peaking at 3’40”. The sequences of frequencies are algorithmically controlled to create temporal situations unplayable on the physical instrument, as with frequency rates as short as 50ms per event. The subsequent frequencies may be further positioned at extreme ends of the spectra and performed with physically impossible dynamic forces. The arch shape also contours the temporal progressions of the jet angle and vibrato frequency parameters. The breath pressure and noise components of the model also remain constant throughout the piece for reasons of stability.

3.5.3 In Secret (2006)

3. En la noche dichosa, en secreto,
que nadie me veía, ni yo miraba
cosa, sin otra luz y guía sino la
que en el corazón ardía.

Juan de la Cruz: *Noche Oscura*.
Public domain.

3. In the happy night, in secret,
when none saw me, nor I beheld
aught, without light or guide, save that
which burned in my heart.

Transl. E Allison Peers.
Public domain.

In Secret is scored for oboe and electronics. The oboist performs without the reed for the most part. Circular breathing, humming, whispering and annunciating the text in the instrument are actions which produce mostly noisy sonorities. Structurally the piece presents a single gesture of pitch emerging from the colored noise. Smooth oscillation between the pitch and airy material is exemplified in the following score example.

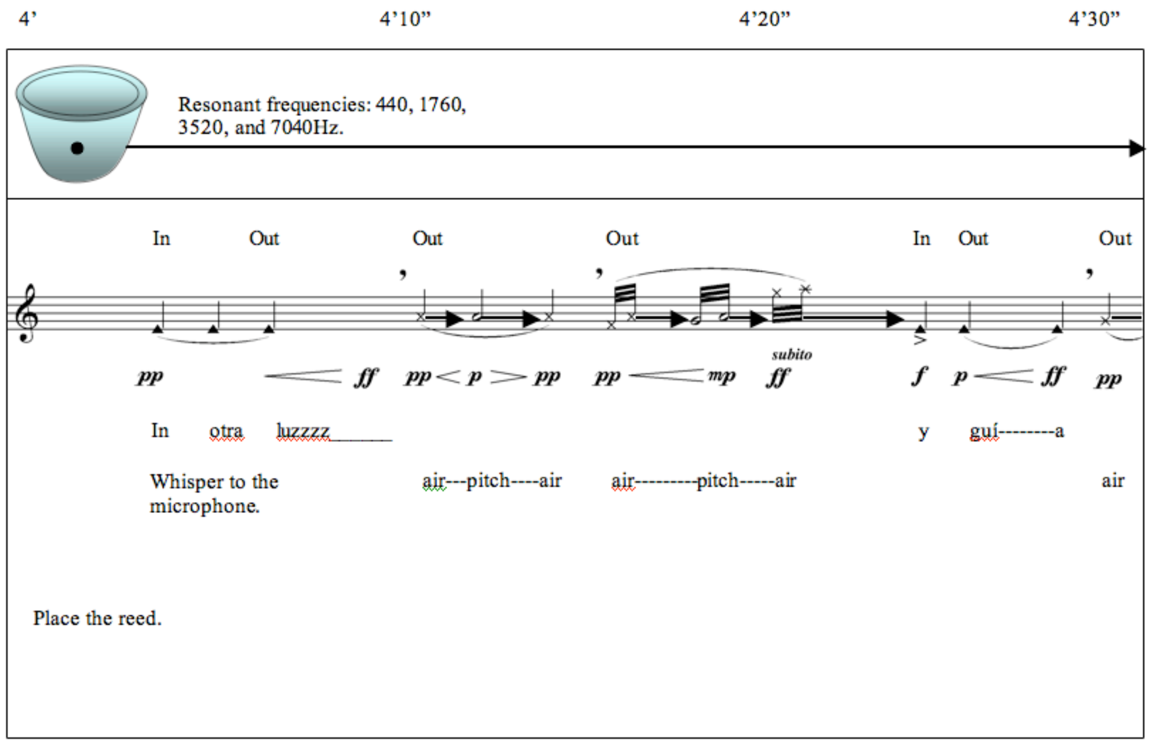

Figure 42. Smooth transitioning between noise and pitch in *In Secret.*

The oboe is amplified, and its signal components also function as the controllers for the parameters of the S. Serafin's singing cyberbowl in MAX/MSP. Key-clicks, explosive outbursts and other gestures excite the cybrinstrument, which complement the residual oboe sonorities with well-shaped frequency spectra. The tones extracted from the poem constitute a set of resonating frequencies for the virtual bowl, which enables fluent transitioning between the frequencies, suggesting fluid deformation of the bowl's body. Changes in the beating frequencies further impart the simulation of continuously changing materials. Figure 43 displays the Tibetan cyberbowl used in this piece.

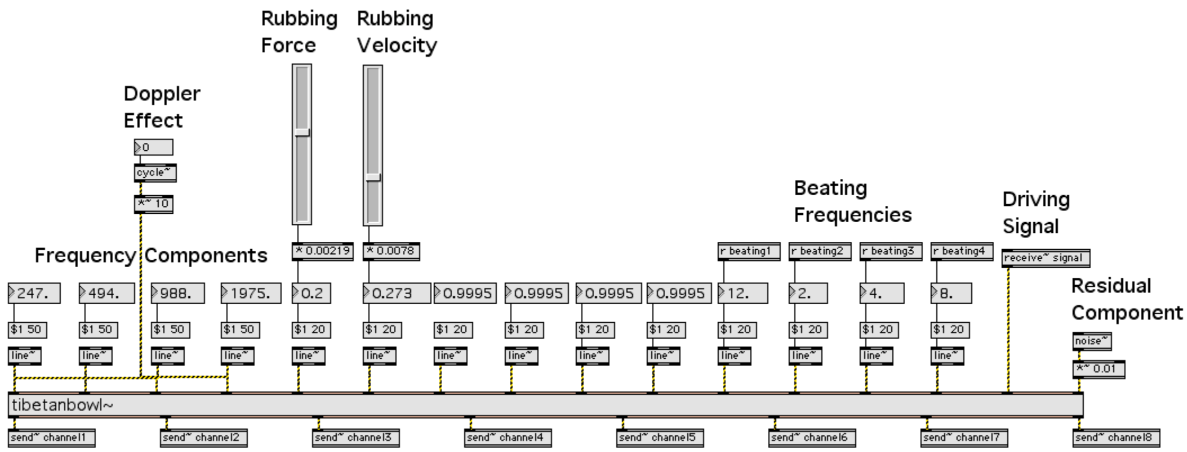

Figure 43. S. Serafin's singing bowl as used in *In Secret*.

The cyberbowl also acts as a resonating space in which the performance occurs. The eight-channel spatialized cyberbowl is further rotated in MAX/MSP, giving an impression of space evolving in a spiral. The composition presents sonic layers of physical and virtual sonic spaces. The sounds of the oboe and cyberbowl thus intertwine to create an augmented sonic reality.

3.5.4 To Where he Waited (2006)

4. Aquésta me guiaba más
cierto que la luz de
mediodía, adonde me
esperaba quien yo bien me
sabía, en parte donde nadie parecía.

Juan de la Cruz: *Noche Oscura*.
Public domain

4. This light guided me, more
surely than the light of
noonday, to the place where
he (well I knew who!) was awaiting me
--a place where none appeared.

Transl. E. Allison Peers
Public Domain

To Where He Waited (2006) for cello and electronics investigates the noisy sonorities that can be produced by the instrument. The entire piece is performed on open strings (for the most part partially or fully muted, creating a rhythmic element from 4'30"—5'25").

The instrument is divided into tail, bridge, fingerboard and nut regions where the cellist performs various circular, longitudinal and traverse actions. Figure 44 shows a page from the score.

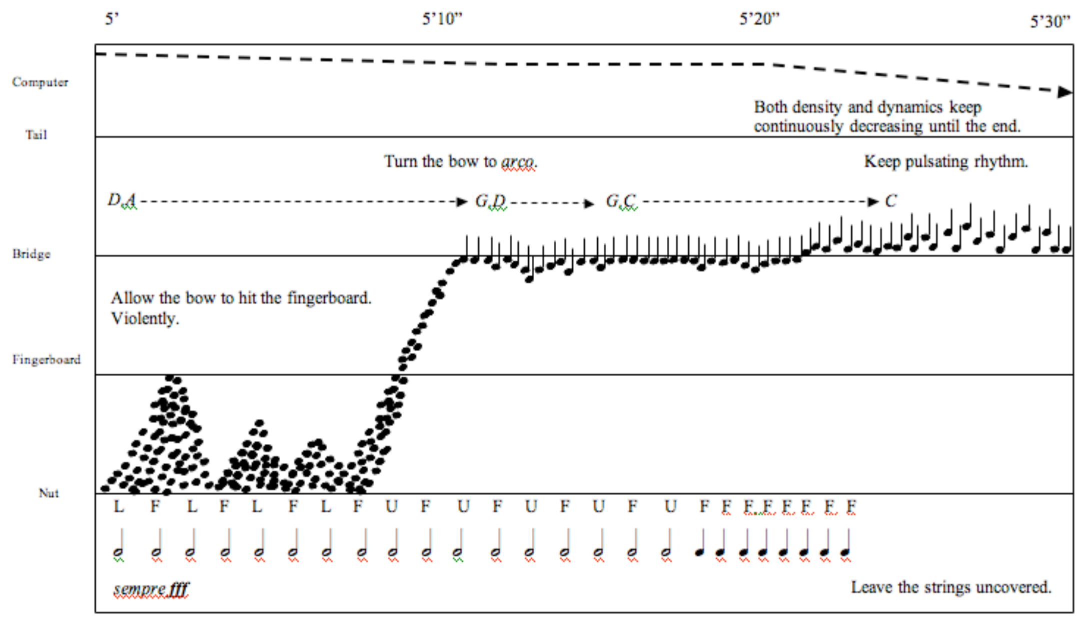

Figure 44. Cello is divided into tail, bridge, fingerboard and nut regions in *To Where He Waited.*

While the opening section (0—50") explores the *arco* bowed sounds on and close to the bridge, the following part (50"—1'40") investigates *pizzicato* combined with static *col legno* and *col legno tratto*. Circular motion in *col legno* style across the strings and regions is first combined with pizzicato (1'45"—3') and then presented as smooth and interrupted gestures along the various strings. A short transition leads to the *col legno battuto* section which lasts from 4'30" towards the end of the cello part at 6' with smooth transition from *col legno* to *arco* at 5'10". The actions move from the bridge area to the fingerboard and then behind the bridge where the piece ends. In fact, the progression of actions described above defines the form of the composition as shown in figure 45.

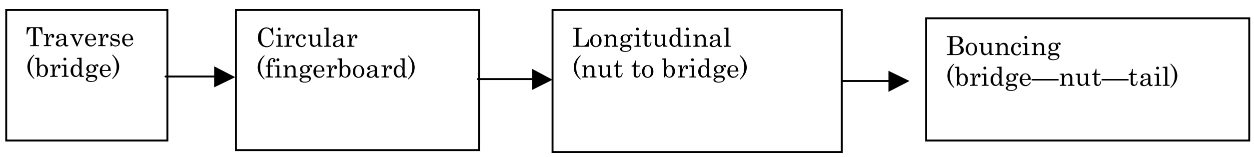

Figure 45. Actions structurally define *To Where He Waited.*

The electronic part uses a percussion cybermembrane which was designed as a two-dimensional waveguide mesh by Scott Van Duyne and Julius Smith (Van Duyne & Smith 1993) and ported to MAX/MSP by Dan Trueman (Trueman & DuBois 2005). This cybermembrane presents a sonic barrier, which is excited by the cello signal, heard only when it passes through this virtual wall. The membranes are tuned to the pitches derived from the letters of the poem.

3.5.5 Guiding Night (2007)

5. ¡Oh noche que
guiaste! ¡oh noche amable
más que el alborada! ¡oh
noche que juntaste Amado
con amada, amada en el Amado transformada!

Juan de la Cruz: *Noche Oscura*.
Public domain

5. Oh, night that
guided me, Oh, night more lovely than the
dawn, Oh,
night that joined Beloved
with lover, Lover transformed in the Beloved!

Transl. E. Allison Peers
Public Domain

The Guiding Night for violin and electronics is somewhat different in character from the rest of the series. The composition explores noise sonorities and actions on the instrument with the dynamic range spanning from *pppp* to violent *tutta sforza* scratch tones. Single crescendo gestures frames this six-minute long composition.

The instrument is divided into performative areas such as tail, bridge, fingerboard and strings in *Guiding Night*. After a one-minute electronics introduction, the violin begins with rocking across the strings close to the bridge and quickly expands the gesture to cover all the performative areas. Pitched materials derived from the letters of the fifth verse appear in the C5 register at 2’15”. As the piece progresses the materials are continuously moved to higher regions reaching E7 at 3’45” and harmonics in the C8 regions at 3’50”. At 4'12" the music abruptly drops three octaves. The motives are then restated in doubled octaves and locked into *crescendo* and *perpetum mobile* trance which culminates at the end.

Guiding Night engages the plucked cyberstring designed by Serafin with the Karplus-Strong algorithm. Figure 46 shows the cyberstring's implementation in MAX/MSP which provides real-time control over parameters such as their impulse/plectrum action generation (the wavetable), resonant frequency, damping factor, harmonicity/inharmonicity parameter and coefficient S for low-pass filter defined by the output $y(n)= S*x(n) + (1-S)*x(n-1)$. The low pass filter affects the sound through slight detuning.

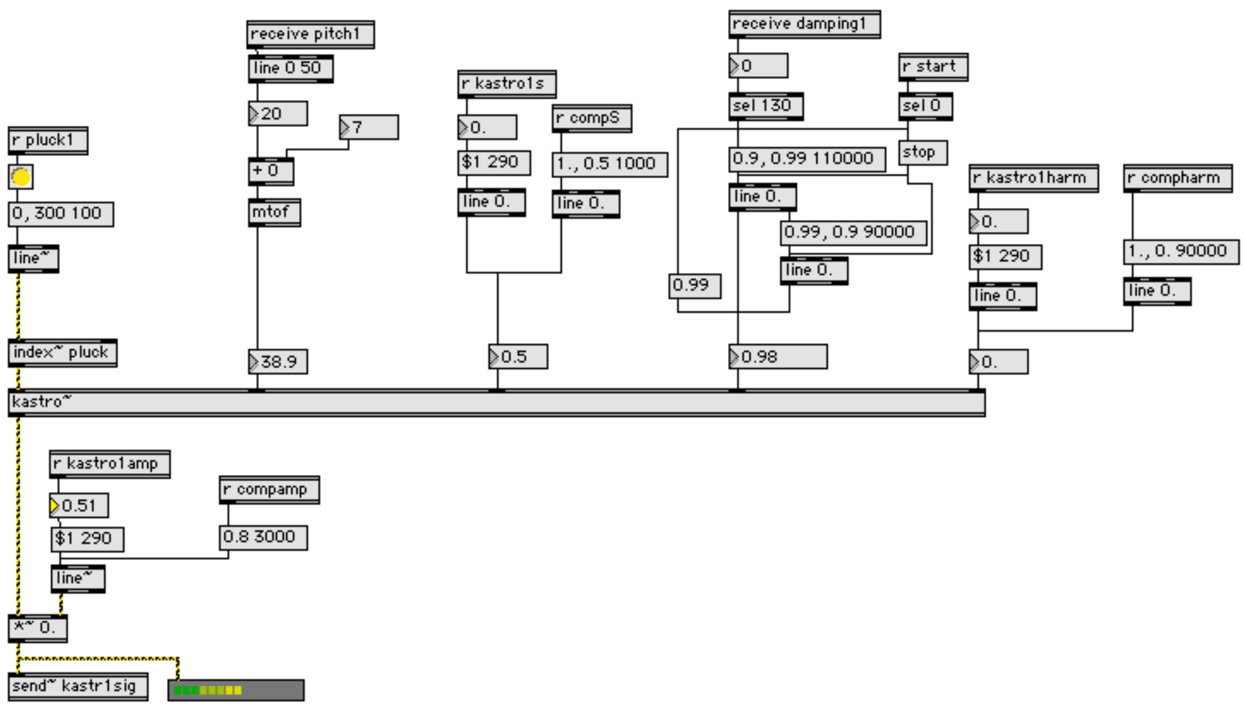

Figure 46. Karplus-Strong plucked cyberstring implemented in MAX/MSP by S. Serafin as used in *Guiding Night*.

These parameters are either controlled in real-time or preprogrammed. The signal from the violinist is tracked, and its amplitude is split into several bands. Each range controls one of the five cyberstrings. The table 8 shows the temporal evolution in mapping of the individual parameters.

Table 8. Control parameters of the plucked cyberstring and their timing in *Guiding Night*.

Parameter	**Control**	**Time**
Plucking mechanism	Preprogrammed	0—6'10"
Frequency	Preprogrammed	0—6'10"
Amplitude	Violin signal	2'10—3'10" then fixed
Harmonicity	Violin signal	3'10"—5' then fixed
S coefficient	Violin signal	5'—6'10"
Damping	Preprogrammed	0—6'10"

The pitches fed to the cyberstrings mirror the material presented by the physical violin. The musical letters are ordered, transposed and rhythmisized. The five lines of transcribed musical letters are shown as five pitch rows in the table 9.

Table 9. The fifth verse of St. John of the Cross' *Dark Night* transcribed into musical alphabet.

Line in the verse	**Letters transcribed as musical tones into pitch rows**
I	B, C, B, E, E, G, A flat, E
II	B, C, B, E, A, A, B flat, E, A flat, E, E, A, B flat, A, D, A
III	B, C, B, E, E, A flat, E
IV	A, A, D, C, A, A, D, A
V	A, A, D, A, E, E, A, A, D, A, F, A, D, A

John of the Cross wrote his *Dark Night* in the form of a *cancion* in the *lira de Fray Luis de Leon* style. Each verse of the poem consists of five to six lines with the following possible arrangements: aBabB, aBaBcC, abbacC, abABcC, etc. The lower case letters represent shorter lines, and the capital letters signify longer lines. An analysis of the poem shows the following version of cancion:a (7), B (11), a (7), b (7), B (11), totaling 43 syllables.

The last line of the cancion style must have a hendecasyllabic meter. The groups 2,4,6; 1,4,7 and their subsets show the potential distribution of the *a* and *b* parts. The accents in the hendecasyllabic verse marked as A, B and C may appear on the following syllables: 1, 4, 7; 2, 6; 1, 6; 4, 6; 4, 8; and 4, 6, 8 with the obligatory stress on the tenth syllable. Accents are avoided on syllables 5 and 9.

Guiding Night takes the form and rhythmical distribution of the *cancion* and applies it in musical terms. The following patterns alternate throughout the composition. The strong long beats are marked as quarter notes, while the short syllables are shown as eight notes.

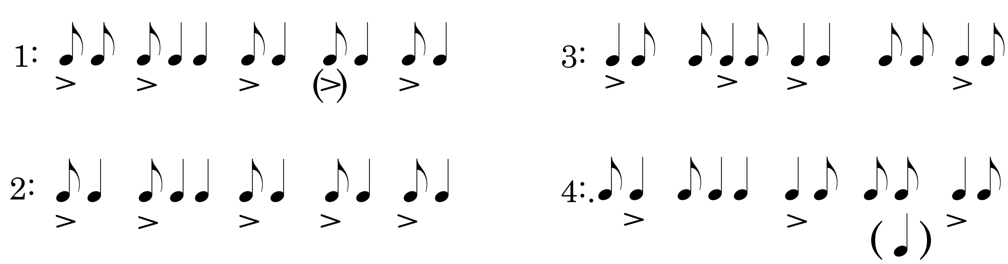

Figure 47. Rhythmic patterns derived from the hendecasyllabic verses used in St. John's *Dark Night*.

Patterns 1 and 2 share accents on 1, 3, 6, (8) and 10th beats. The following table shows the internal structures of all the iterations. Note the progressive addition and subtraction in the number of stress beats, suggesting the increasing and decreasing density of the materials: each accented beat initiates a change of pitch. Additionally, the last column suggests the pitch pattern assigned to a particular rhythmic iteration.

Table 10. Structural distribution of rhythmic and pitch material in *Guiding Night*.

Iteration	A	B	A	B	B	Number of changes	Time in 43" increments	Pitch row
1	1,6	1,4,6,10	1,6	2,6	2,6,10	13	43"	I
2	2,4,6	1,4,7,10	2,4,6	2,6	4,6,8,10	16	1'26"	V
3	2,4,6	4,6,8,10	2,4,6	1,4,7	1,4,7,10	17	2'09"	II
4	1,6	1,4,6,10	1,6	2,6	2,6,10	13	2'52"	I
5	2,6	4,8,10	2,6	4,6	4,6,10	12	3'35"	II
6	1	2,10	1	2,6	1,6,10	9	4'18"	III
7	2	6,10	2	4	8,10	7	5'01"	IV
8	6	10	6	1	10	5	5'44"	I
9	1,4,7	1,4,7,10	1,4,7	2,4,6	4,6,8,10	17	6'27"	V

If the rhythm pattern possess more accented beats than available pitches, the pitch row is looped to fill the missing beats. If the rhythmic pattern has fewer stressed beats than the pitch row, the pitch row is truncated.

While the violin sonorities are concealed by noise the cyberstrings present clear pitch material. Plucking actions define the character of the piece as primarily rhythmic and augments the pitch, timbral and performative aspects of the physical violin playing. Plucking the strings at almost sub-audio rate suggests a cyberstring of parametrical dimensions non-existent in physical reality. The continuous changing of the string's material properties, such as harmonicity and damping, introduces additional timbral extensions. At the same time detuning the cyberinstruments while plucking them in rapid tempi suggests performative actions which stretch the restrictions of the physical performance. The result is a composition which pushes both the physical and cyberinstruments to their limits, is an intense contest between the live performer and computer.

3.5.6 There He Stayed (2007)

6. En mi pecho florido, que entero
para él solo se guardaba, allí quedó
dormido, y yo le regalaba, y el
ventalle de cedros aire daba.

Juan de la Cruz: *Noche Oscura*.
Public domain

6. Upon my flowery breast,
kept wholly for himself alone, there he stayed
sleeping, and I caressed him, and the
fanning of the cedars made a breeze.

Transl. E. Allison Peers
Public Domain

There He Stayed is a composition for everyday objects and voices. The piece is based on the text of the sixth verse from St. John of Cross' *Dark Night* and its hendecasyllabic structure. As in *And All My Senses Suspended*, this piece does not involve any electroacoustic elements.

This composition investigates vocal sonorities and sonorities of everyday objects that lie on the border of hearing. The voices predominantly produce whispers and colored noise. Each choir member operates an empty two-liter plastic bottle, the bottle's top, a pencil and a sheet of paper, and manipulates, molds and even breaks these everyday objects to complement the noisy vocal sounds. Some of these actions are shown in the following figure.

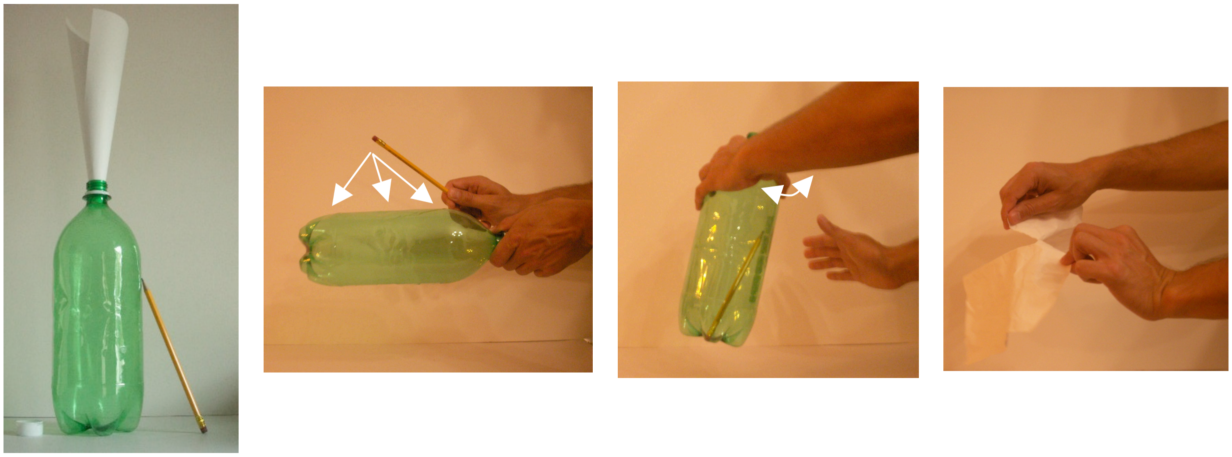

Figure 48. Examples of performative actions in *There He Stayed.*

The composition's structure has eleven parts, each of which signifies a long or short syllable in the hendecasyllabic meter. Each section elaborates a particular action such as blowing inside the bottles and manipulating paper. The duration of each part measured in beats is a multiple of eleven. Vertically the choir is always divided into parts and groups, with the same (or almost the same) number of voices in each group. Each of the parts performs different musical material and should be occupied by the same number of performers. The number of groups increases as the composition unfolds, continually shifting the balance of the parts. Each choir member is assigned a part at the beginning, which may be regrouped in the course of the piece, so at least twenty-two voices are needed. Eleven of these always cover the core parts and the other eleven jump between the groups. The following figure shows the organization of the piece.

Sections Number/ Parameter	1	2	3	4	5	6	7	8	9	10	11
Hendeca-syllabic beats	Short Stressed	Short Unstressed	Short Str.	Long Unstr.	Long Unstr.	Short Str.	Long Unstr.	Short Str.	Long Unstr.	Short Unstr.	Long Unstr.
Number of beats	22	33	44	66	77	88	99	110	33	33	55
Action	Blow bottles	Blow bottles	Blow bottles	Squish, tap, hit bottle	Perform with paper	Tear paper	Breath and whisper	Gibber and speak	Combine all actions	Speak in bottle	Whisper in bottle
Group subdivision											

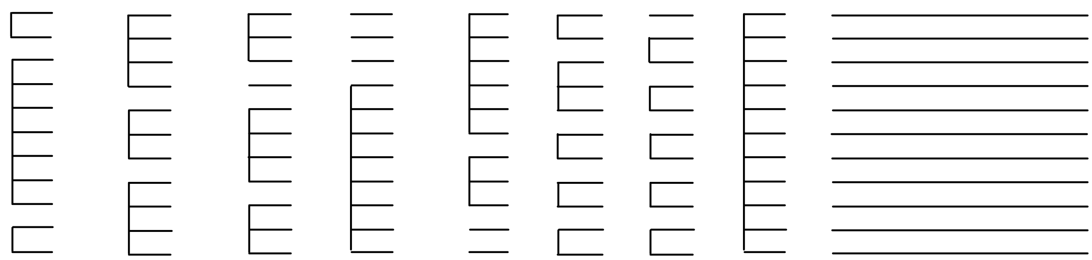

Figure 49. Structural subdivision of *There He Stayed* into 11 parts.

There is no limit as to how many voices beyond these twenty-two can perform this piece, and in fact a larger ensemble is preferred, as it accentuates the composition's delicate sonorities. Amplification of the smaller ensemble is particularly recommended. The following figure demonstrates a situation in which the number of parts equals the number of groups (eleven).

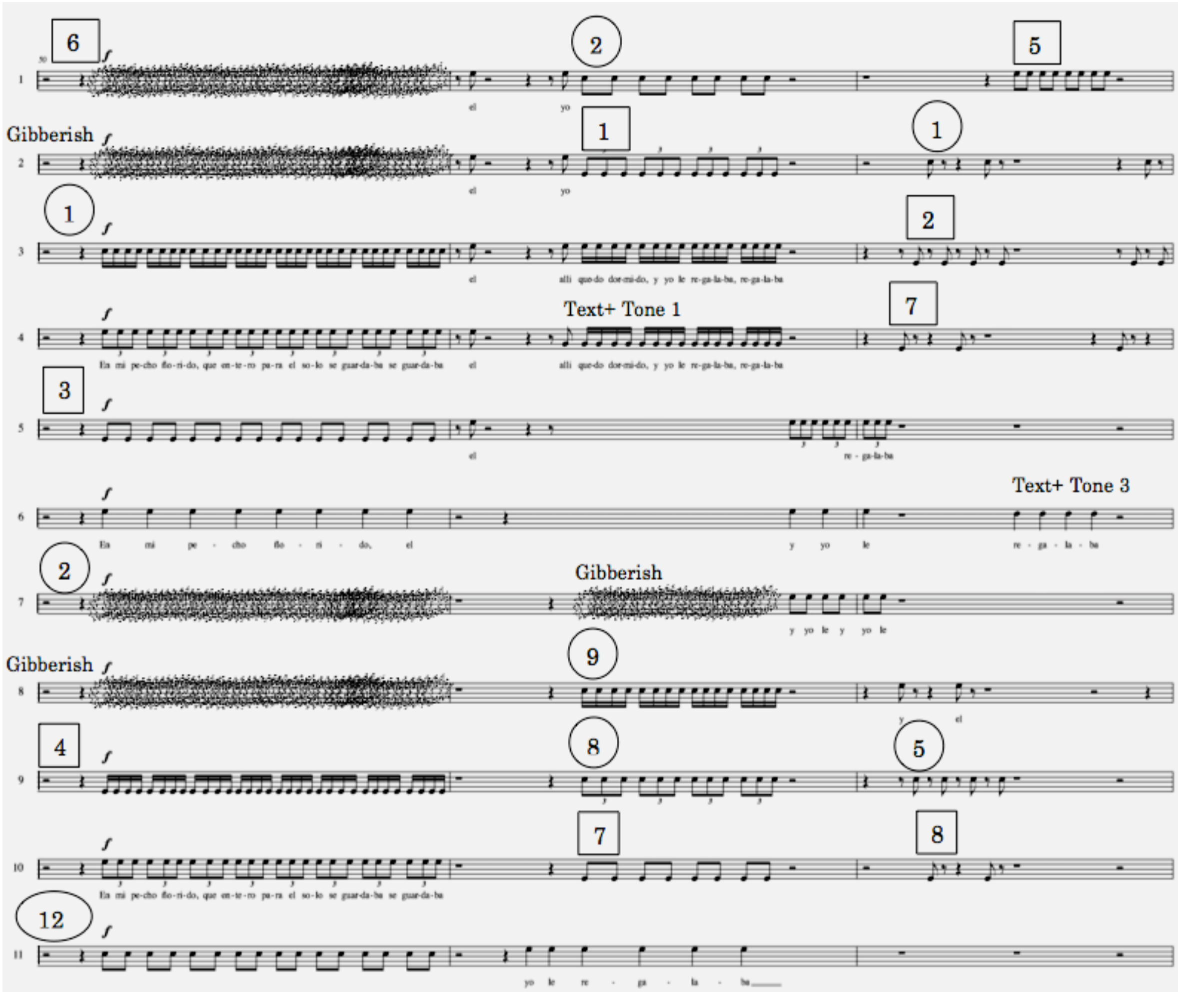

Figure 50. Variety of materials performed by 11 *divisi* groups.

The climactic annunciation of the text in measures 44—49 emphasizes the fundamental role of the poetry in the compositional process. The complete verse is repeated in unison while transitioning from whisper to shouting here. After the grand pause, the decrescendo leads to a diversified performance mode and the dissolution of the sound to silence.

3.5.7 And All My Senses Suspended (2007)

7. El aire de la almena, cuando yo
sus cabellos esparcía, con su mano
serena en mi cuello hería y todos mis
sentidos suspendía.

Juan de la Cruz: *Noche Oscura*.
Public domain

7. The breeze blew from the turret as I
parted his locks; with his gentle hand
he wounded my neck and caused all my
senses to be suspended.

Transl. E. Allison Peers
Public Domain

Based on the seventh verse of the poem, *And All My Senses Suspended* is scored for the flute, electric guitar, double bass and piano. Like *En Una Noche Oscura* the actions are embedded in the score as shown in figure 51. The instrument handling by the performers is choreographed, and in contrast with the other pieces, concrete melodic materials are also presented. The whole ensemble, furthermore, whispers the text in the final section of the composition.

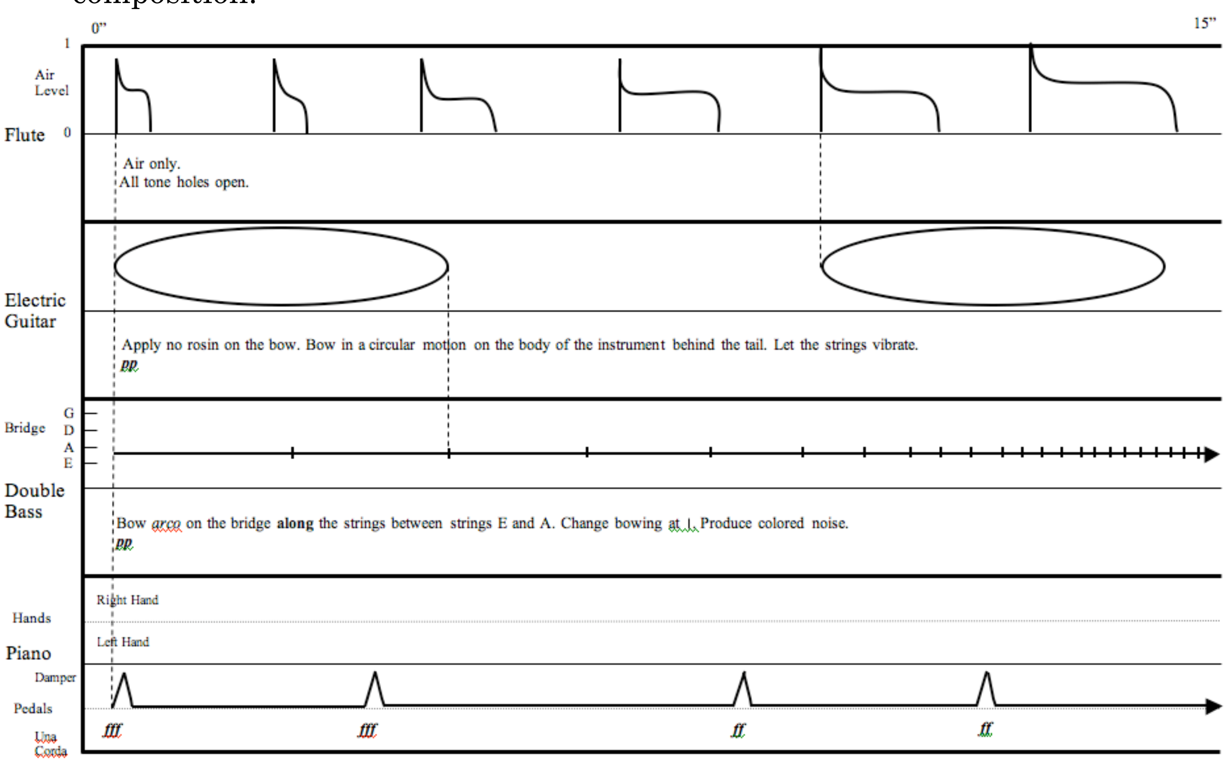

Figure 51. Actions embedded in the score of *And All My Senses Suspended.*

This piece introduces a more elastic approach to material pacing. While two actions may be notated with exactly the same graphic gesture, their duration will depend on the duration of the page where they are located. The score uses a variable page length which fluctuates between 10-, 15-, 20-, 25- and 40 seconds, with the duration increasing toward the end of the composition. Formally, this approach enables elastic pacing of the musical material.

The piece opens with smooth and continuous actions producing colored noise (0—1'). Each instrument establishes a rhythm, which falls in and out of phase from the ensemble. The following section introduces actions of erratic nature culminating at 1'30". The next 50 seconds of music present solos and duets of sustained gestures utilizing explicit pitch textures. The material changes into a maniacal jungle of asynchronized gestures between 2'20" and 3'40" with a tendency toward shorter page segments. The additive process restarts at 3'40" with the re-introduction of the pitched motives and develops into synchronized rhythms at 4'10", and the composition first introduces the text by flute at 4'18", which then expands across the ensemble as the piece moves towards its conclusion. The score reflects the overall *ritardando* of this final section as a continuous extension of the page duration (4'10"—6').

Expressive compactness, attentiveness to detail, strict control over all performance aspects and the virtuosic nature of each part characterize *And All My Senses Suspended*, a composition which is especially concerned with action. Repeated gestures become musically meaningful when grouped into rhythmic patterns. To accentuate the action-based language, the contrasting pitch material is inserted in the center of the piece.

3.5.8 All Forgotten (2006)

8. Quedéme y olvidéme, el rostro
recliné sobre el Amado, cesó todo y
dejéme, dejando mi cuidado entre las
azucenas olvidado.

Juan de la Cruz: *Noche Oscura*.
Public domain

8. I remained, lost in oblivion; My face
I reclined on the Beloved, all ceased and
I abandoned myself, leaving my cares
forgotten among the lilies.

Transl. E. Allison Peers
Public domain

All Forgotten, the final composition of the series, is scored for piano and electronics. With the sustain pedal depressed throughout the piece, the performer plays solely inside the instrument: the hammer-string interaction is completely eliminated. A desire for the closest possible contact between the performer's fingers and the instrument results in the composition's bowing, scraping and plucking actions, with rosined fingertips becoming bows as they slide on the strings longitudinally. The strings are divided into regions and are bowed either as a group with palms or individually with fingertips as shown in the following figure.

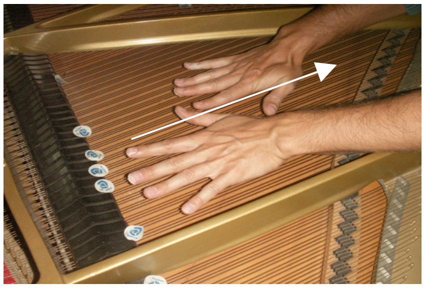 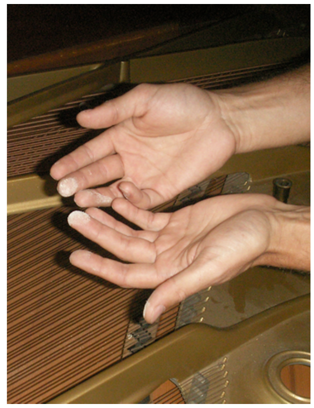 

Figure 52. Bow string regions with palms. Apply resin on fingertips and bow individual strings.

The composition opens with the palms bowing in the C3 region. The musical material of the four lines from the eighth verse is announced between 33" and 3'04" with the accents positioned on strong beats as in the hendecasyllabic meter. After a short transition with bowed palms, the four are repeated an octave lower and rhythmically condensed between 3'38" and 5'14". Scraping the strings with the fingernails (5'36"—6'20") provides a transition to the final portion of the composition which investigates the tapping on the muted or unmated strings with palms while descending through the piano string registers (6'38"—8'40"). The plucking of the low A followed by a tapped rhythmic statement creates a trans like pattern which repeats and eventually dissipates into silence. Figure 53 presents an example from the score.

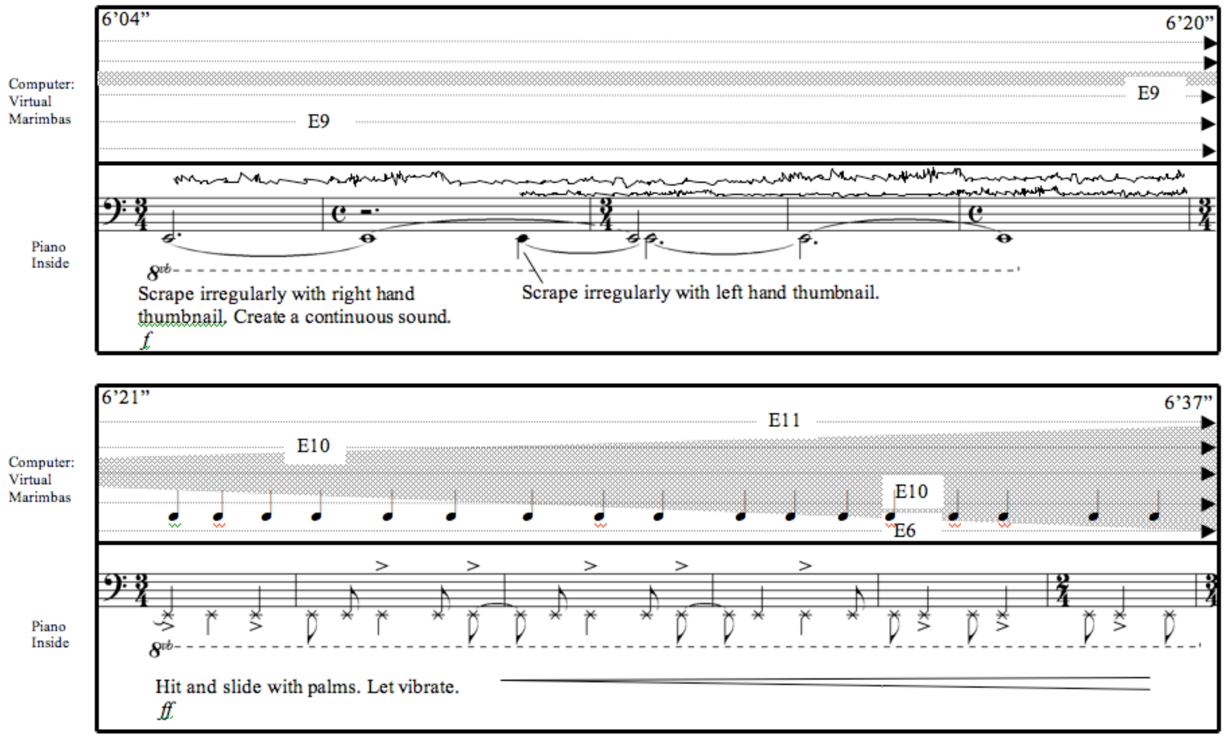

Figure 53. Scraping the piano strings followed by tapping on them in *All Forgotten.*

As in previous works the instrument produces colored noise, which is paired with the concrete pitch materials presented in the electronics. The electronic part uses cybermarimba designed with modal synthesis and implemented in MAX/MSP by Stefania Serafin. Both piano and cybermarimba pitch materials correspond with the 'musical' letters extracted from *Dark Night's* eighth verse. The alphabet letters are directly mapped to the musical pitches, however, and their registration varies. The pitches for cybermarimba are stored in look-up tables which are recycled at various speeds and transposed throughout the composition. While the piano textures descend over four octaves in nearly nine minutes, the electronics ascend to registers beyond the range of the piano keyboard.

Extending the cyberinstrument's possibilities, the virtual marimbas enable the production of high and low tones not performable on the physical instrument, the sustained excitation of those tones, otherwise unfeasibly rapid tone repetition (as fast as one event per one millisecond), the real-time change of the beater qualities, and the extremely rapid repositioning of the beater on the bar. While straining the physical piano and cybermarimbas, *All Forgotten* contemplates the suppressed beauty hidden in the tension of the string and mass of the cyberbar.

3.6 Neither Stirred, Nor Shaken (2007)[20]

Research discussing the influence and potential health benefits of stirring over shaking in the preparation of the martini cocktail inspired this piece (Trevithick et al. 1999). The composition *Neither Stirred, Nor Shaken* for cocktail glasses, shakers, blenders and electronics uses physical actions such as the stirring, shaking and mixing of those everyday objects along with sensors and cyberinstruments using physical modeling synthesis. Three performers stir liquids and ice with metal spoons in highball cocktail glasses, shake their concoctions in metallic shakers, and mix them in electric blenders; these physical objects are coupled with the cybershakers and

[20] Some aspects of the composition are described in *Stirring, shaking, and mixing: Musicalizing everyday actions* (Kojs and Serafin 2007a) and *Everyday objects in interactive electroacoustic compositions* (Kojs and Serafin 2007b).

cyberrattles and singing bowed cyberglasses in order to create a rich timbral tableaux.

Neither Stirred, Nor Shaken utilizes sensor technologies connected to the Make Controller board in order to acquire data from the everyday objects. The Make Controller board is attached to a computer running MAX/MSP via a USB cable (MakingThings 2007). The setup for each player consists of a highball cocktail glass, a tall metal spoon, metal shaker, two-speed five mode electric blender with a pulse function, ice, clear liquid, sensors and a Make Controller board as shown in figure 54.

Figure 54. Instruments and sensors used in *Neither Stirred, Nor Shaken*.

I used a temperature sensor, accelerometer and piezo sensor to track in real-time some of the physical parameters of the cocktail-making. The temperature sensor is implanted in the used CD case serving as a glass stand which protects the sensor from dampness of the cocktail glass. The accelerometer is interlaced into the textile wrist-band. The performer wears the wrist-band on the palm of the hand with which he/she operates the shaker. The piezo sensor is taped to the engine exhaust outlet of the electric blender. All of the sensor technologies are displayed in the following figure.

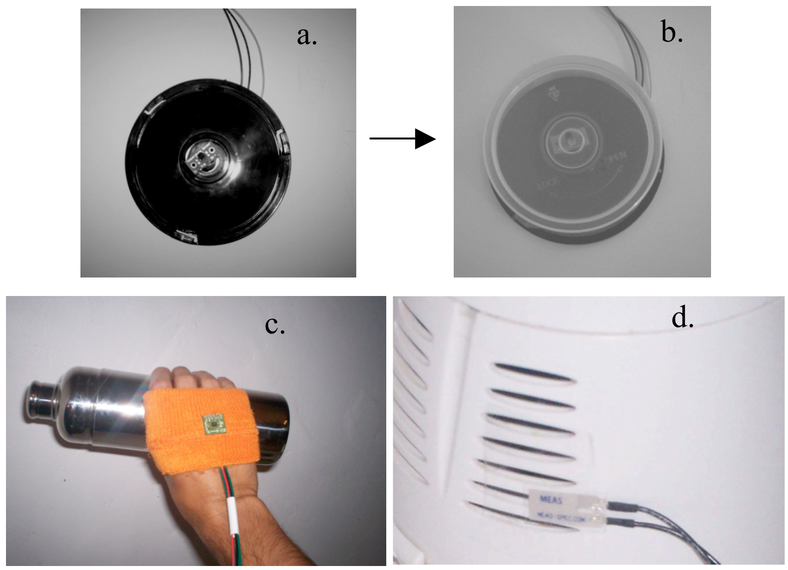

Figure 55. Sensor technologies used in *Neither Stirred Nor Shaken*: The temperature sensor (a) placed and (b) inserted in the plastic CD case, an accelerometer woven into a textile wrist-band (c) and a piezo sensor attached to the exhaust outlet of an electric blender (d).

The piece is structured in three parts which are dominated by stirring, shaking or blending, each of which produces a cocktail. In the opening section, the performer places a cocktail glass with ice and liquid on the CD case covering the temperature sensor and stirs the liquid. The sensor measures the temperature decrease of the liquid throughout the nine-minute composition. Each player stirs different number of cubes (5, 10 and 15), resulting in slightly different temperatures. In section two, the three performers shake the liquids and ice using metal shakers. An ADXL 330 triple axis accelerometer (Sparkfun 2007) tracks the acceleration of the moving hands. In the final section, the performers use three electric blenders. The piezo sensors (LDT0 solid state switch/vibration sensors) track the varying air pressure exiting the blenders via their exhaust grids. The resulting data depends on the amount of liquid and number of ice cubes in the blenders.

The players taste the drinks prepared during the performance and arrange them according to their quality at 7'. One of the player inserts the quality-order data into a MAX/MSP patch which evaluates the data and chooses one of the three potential solo-electronic conclusions. The complete sensor set up is displayed in figure 56.

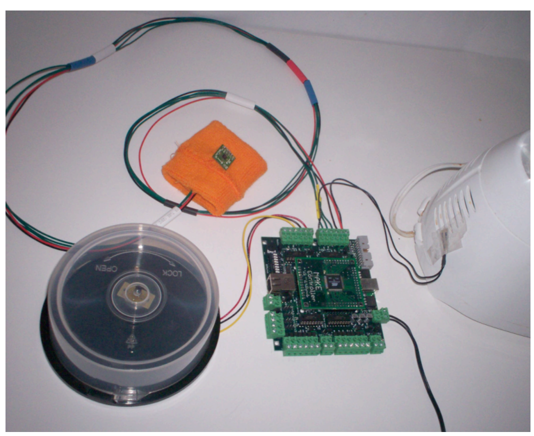

Figure 56. Sensors connected to the Make Controller board in *Neither Stirred Nor Shaken.*

Sensor data is used to control the cybershakers, cyberrattles and singing cyberglasses. Serafin created cybershakers and rattles with the PhISEM algorithm (Cook 1997) and cyberglasess with the banded waveguide synthesis (Serafin et al. 2001). While the shaking actions excite the cybershakers, hitting and rubbing can activate the cyberglasses in MAX/MSP. The analog actions are tracked and converted to digital data in MAX/MSP as shown in the following tracking interface.

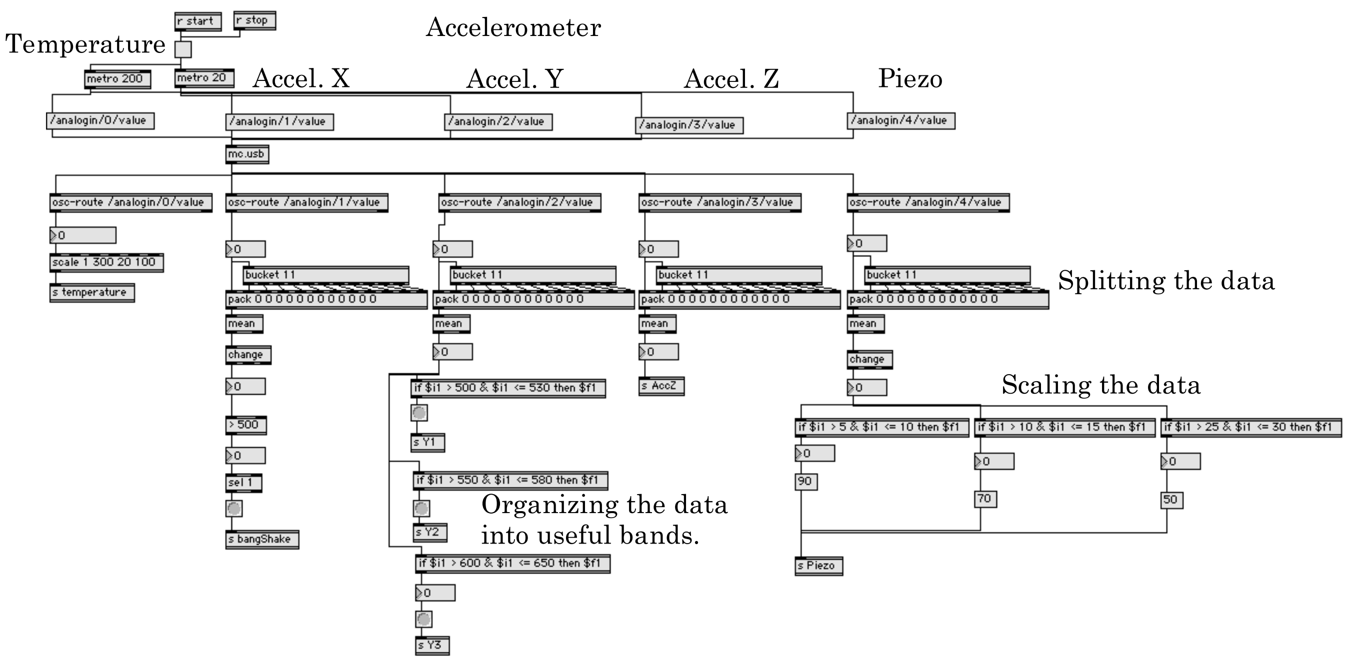

Figure 57. Data tracking interface in MAX/MSP.

The physical and cyberinstruments are paired according to the sections in which they are used, and their parameters are mapped accordingly. Figure

58 portrays the temporal development of actions and technologies in the piece.

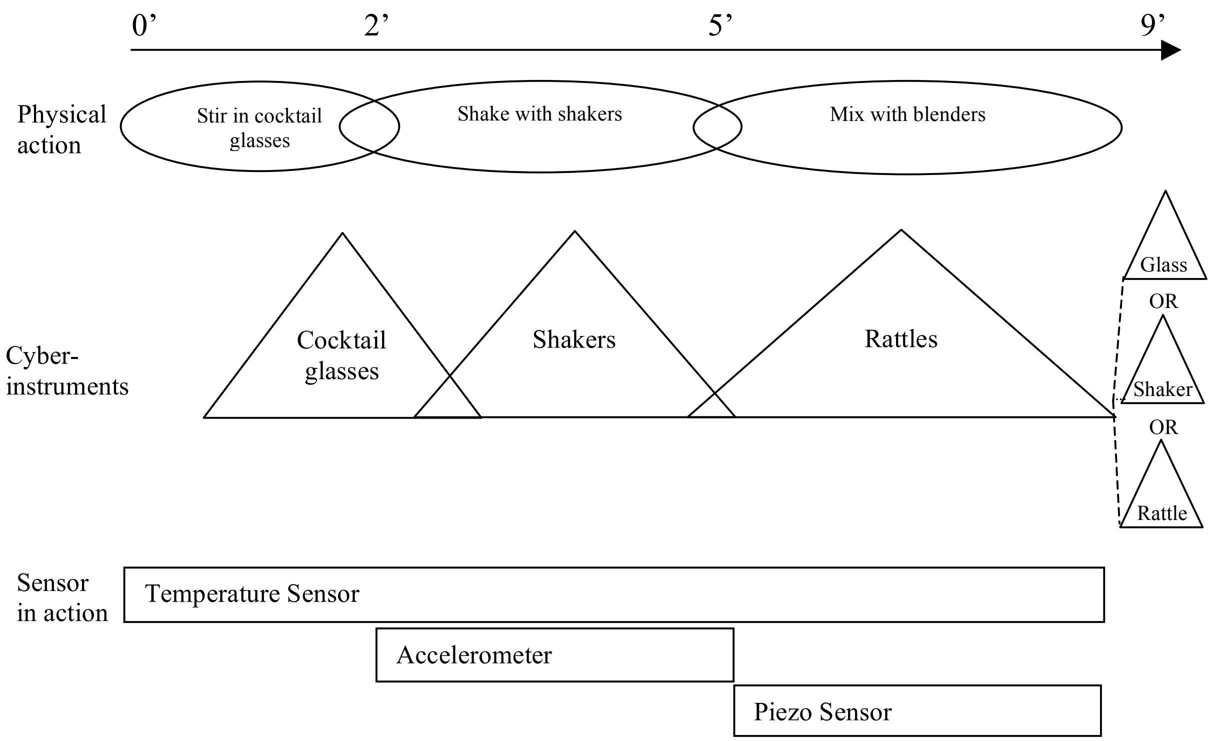

Figure 58. Temporal Alignment between physical actions, cyberinstruments and sensor technologies in *Neither Stirred, Nor Shaken.*

Neither Stirred, Nor Shaken highlights initiation, transformation and transportation of energy manifested in the stirring, shaking and blending which trigger the transformation of ice to liquid. The melting process is also reflected in the pitch design of the composition. The frequency spectra imitate a river-like form with multiple frequencies appearing at the beginning of the piece and converging to create a louder yet less dense pitch structure. The resonant frequencies of the cybershakers, rattles and glasses are derived from the spectra of the physical action sounds.

The following figure shows the first 2’20” of the composition’s pitch plan. The pitch skeleton defines the musical structure of the piece, though each reiteration of *Neither Stirred Nor Shaken* will be slightly different depending on-conditions such as ice cube size, shaker material and blender model.

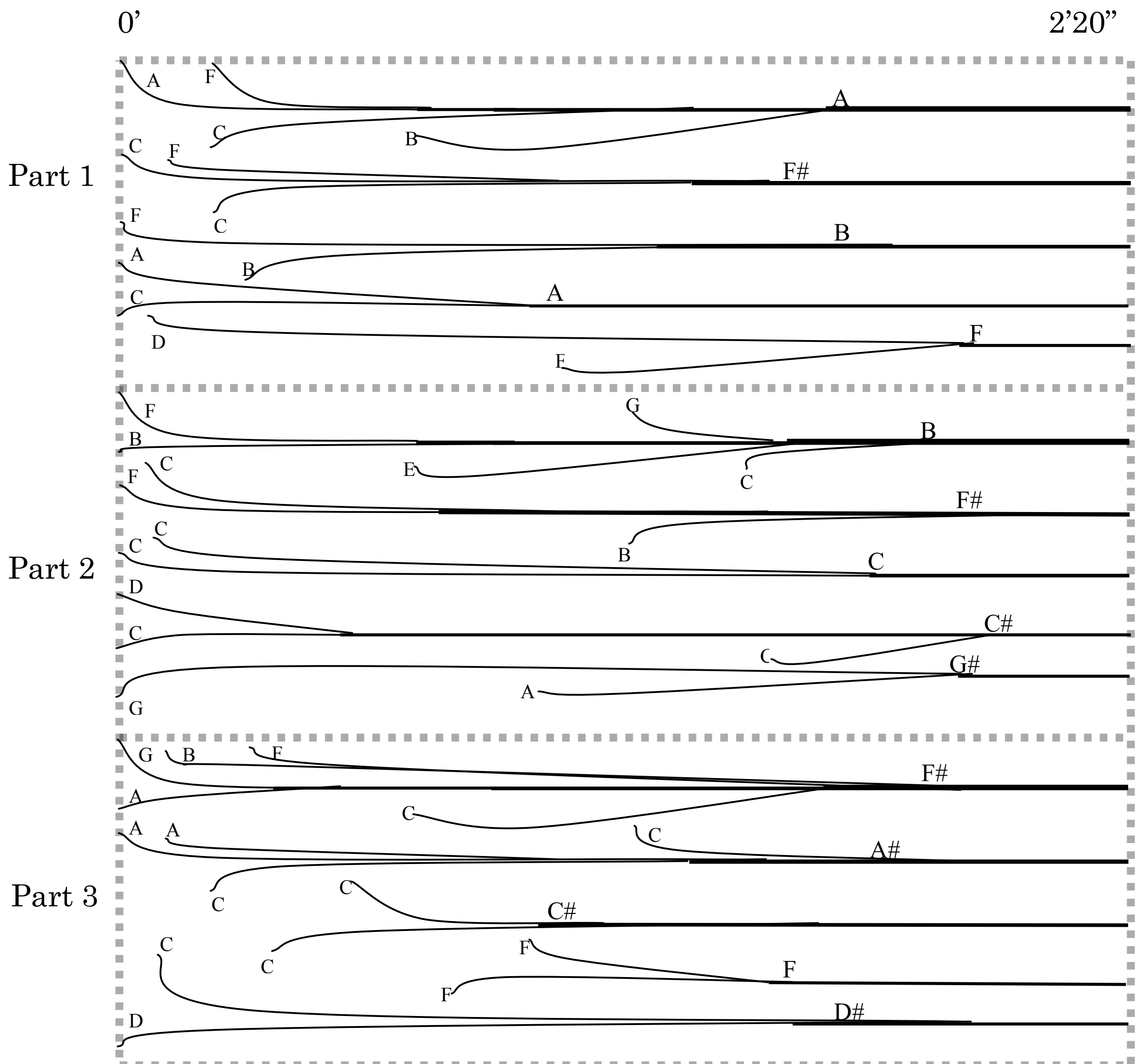

Figure 59. Pitches converge during the composition creating dense-to-thin spectral textures.

3.7 Zvonenie (2007)

Zvonenie (Ringing) is orchestrated for cyberbells on 4-channel speakers. The composition situates the Slovak sheep bell, an ancient folk instrument, in the domain of digital technology. The composition developed from the idea of digital excavation and the preservation of the bells from rural Slovakia.

Sheep bells arrived in Slovakia during the shepherd colonization in the 13th century by the Wallachians of Romania. In the northern region Liptov, where I grew up, sheep bell production has flourished since the sixteenth century (Zuskinova 1999). Following twentieth century industrialization and the disappearance of small farmers, sheep breeding and shepherding culture and its sounds became increasingly rare in the Slovak countryside.

From my early childhood I remember the sounds of clanging bells at my grandfather's farm. All the bells were tuned to one common tone. This way the shepherds, who pastured and guarded the animals in the spring and summer, could identify the sheep in case they mingled with other herds which were tuned to other tones. Consequently, it was important for the farmers to get a set of well-tuned bells. A resonant bell was often more valuable than the sheep itself. An example of a large Slovak sheep bell is shown in the following figure.

Figure 60. A large Slovak sheep bell made of brass (450g in weight) usually worn by muttons.

The process of composing *Zvonenie* began with the study of a physical sheep bell's acoustics. The spectrum of the bell became the primary source for the horizontal and vertical structures of the composition. The digital simulation of the bell via physical modeling and extending its properties beyond the limitations of the physical world followed.

I designed the cyberbells using GENESIS software at the ICA—ACROE center in December 2006. GENESIS is a composer-oriented interface designed for building physical models within the CORDIS–ANIMA environment as described in chapter 2.[21]

GENESIS enabled me to not only digitally replicate the sounds of the physical bell, but also to extend its properties beyond the limitations of the physical world, facilitating simulations of the cyberbell structures made of materials such as metal, glass, wood and their various combinations.

[21] GENESIS is a composer-oriented interface designed for building physical models which enables a creation of modular, freely re-combinable, virtual structures and networks. (Castagne and Cadoz 2002).

Additionally, I used actions such as hitting, bowing and plucking to excite the bells.

Figure 61 exemplifies a basic cyberbell structure in GENESIS. The bell is constructed of 11 masses (yellow dots) which are connected with the damping-stiffness links (blue lines). Blue dots are masses ground~~ed~~ to a fixed point. The pink square is a cybermicrophone module which enables us to hear the instrument, and the beater consists of a fixed point (the green dot) connected to a mass. The nature of the cyberaction between the beater and instrument (blowing, bowing, hitting and plucking, etc.) is defined by the connecting link. In this case, the red link and its parameters signify hitting.

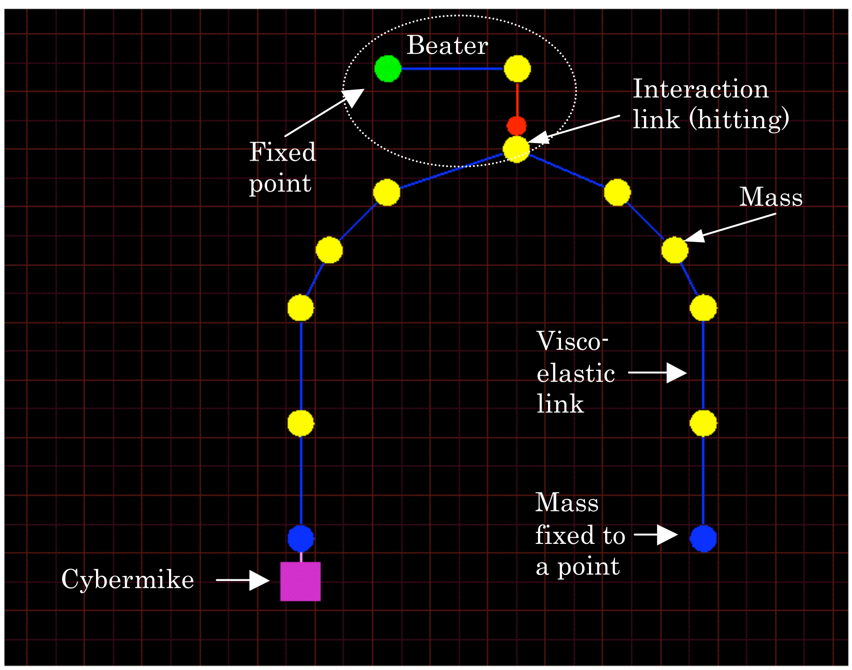

Figure 61. A simple cyberbell structure.

These various interactions generated complex rhythmic sequences. For instance, two "cyberarms" operating two mallets with nonlinear behavior excited four cyberbells cloned from the original instrument to generate gamelan-like rhythmic structures. Figure 62 displays a simulation of a performer with two arms hitting four cyberbells.

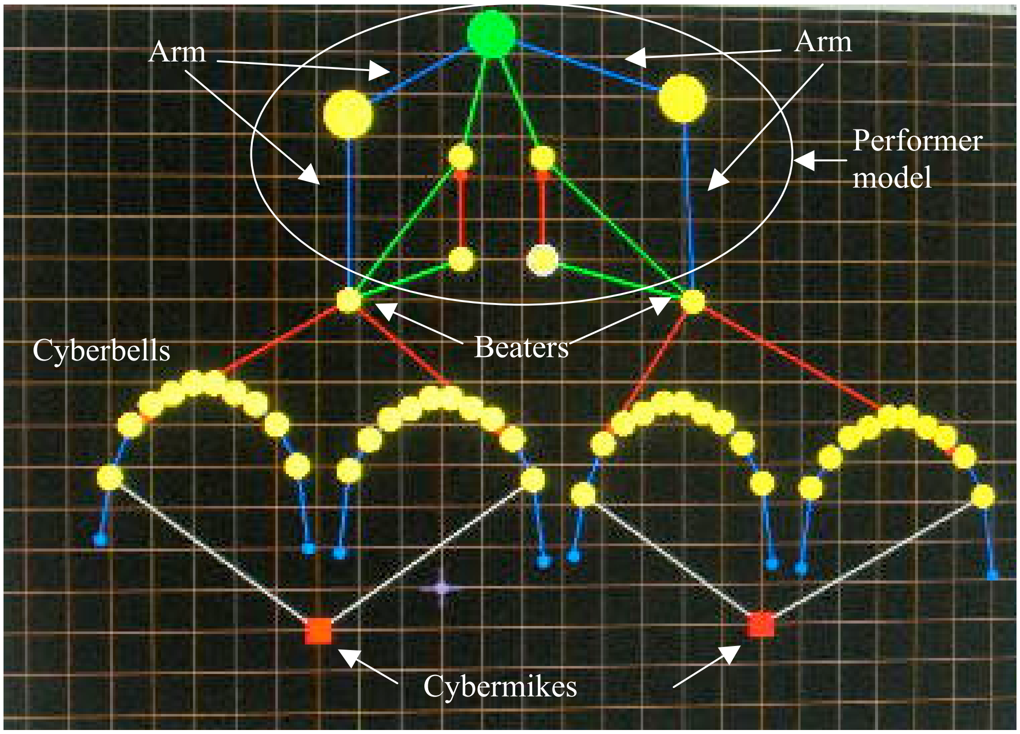

Figure 62. Four cyberbells in the GENESIS bench.

Changing the character of the links within the exciter (the arm apparatus and beater) facilitated the creation of performance modes such as hitting, bowing and plucking. I highlighted particular sonic properties of the sounding cyberstructure with specific virtual speaker placement.

Setting the exciter into motion resulted in the creation of complex rhythms. While the initial sonic behaviors are chaotic they develop in the course of the composition into synchronized patterns. To ensure the synchronization of motion, I simulated the exciter to produce rhythms derived from a subdivision of quarter note equaling 60bpm.

The rhythmic sequences I generated featured one of the four timbral qualities: metal hitting, bowed and plucked metal, plate-like hitting and wood-like hitting, all exported from GENESIS as audio files in the .aiff format. According to the number of resonating models, the files were either mono (with single bell), stereo (with two bells), or quadraphonic (with four bells). The application of dynamic spatialization and reverberation in MAX/MSP completed the work.

I completed the final formal organization in the GarageBand digital studio. To remain truthful to the idea of complete physical modeling use, the processes included only cutting, alignment and dynamic layering, and the density of sounds ranged from a single voice homophony to 20-voice polyphony. The general density trajectory is displayed in the following figure.

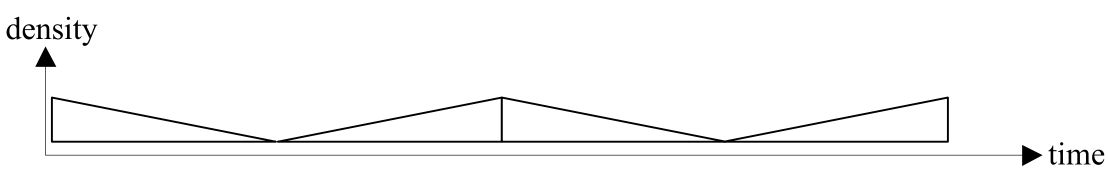

Figure 63. General density trajectory in *Zvonenie*.

The form of the composition follows a trajectory in which the bell materials, shapes and interaction change to produce novel timbres, as shown in the figure 64. The pitch structures, which were derived from the spectrum of the physical bell and remained fixed throughout the piece, result from the non-linear interactions between the exciters and cyberbells.

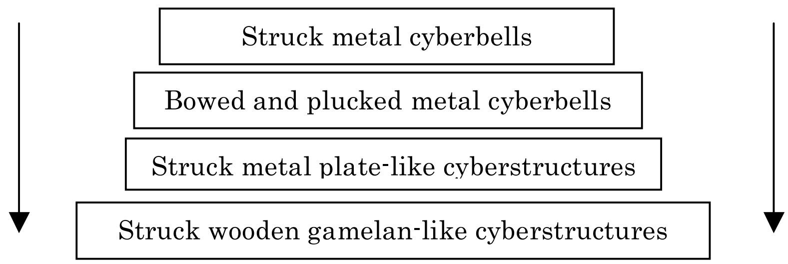

Figure 64. General timbral trajectory.

As stated above, the audio was exported in the form of audio files from GENESIS. I grouped the resulting twenty files and dynamically spaced them into four layers of five files as shown in figure 65. The layers closer to the center are dynamically more present and vice versa.

I then exported these layers from GarageBand as four stereo files, and spatialized them in MAX/MSP using the ambisonic approach. General 360-degree rotation of the four groups is programmed according to a simple algorithm: 4 rotations * 4’22”= 13’28” (the total duration of *Zvonenie*). Groups one and three rotate in clock-wise motion (0—360 degrees in 4’22”), while groups two and four rotated in the counter clock-wise motion (360—0 degrees in 4’22”). The sound sources either rotated or remained stationary, which enriched the contrapuntal spatialization motion.

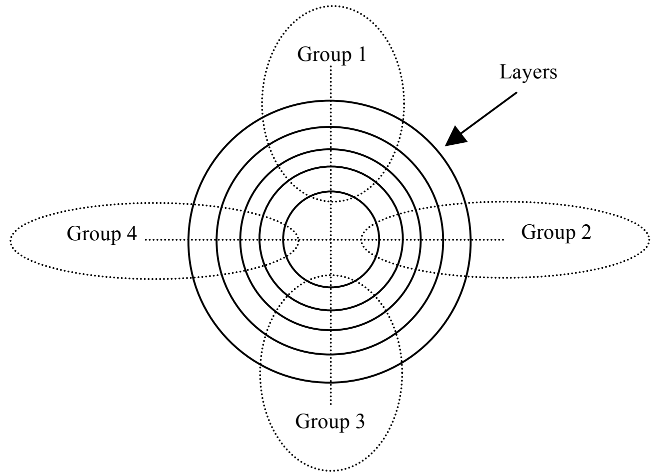

Figure 65. The points where the full circles interject with the dotted lines represent the dynamic positioning of the twenty files. The sounds closer to the center are more prominent and vice versa. The 'Groups' suggest the quadraphonic dispersion of the sound.

The complex arrangement of the background, middle ground and foreground expanded the *internal* multidimensionality of the resulting sound. The dynamic emergence and disappearance of particular sonic layers served as a technique to simulate a pulsating organism. Additionally, the reverberation engine in MAX/MSP facilitated the softening of the synthetic sonorities and creation of *external* projection space.

Zvonenie thus strives to remain in touch with the physical reality of the sounding sheep bells. GENESIS enabled me to alter the cyberbell materials and consequently change the bells timbres, however, and they were thus able to generate impossible performance cyberactions resulting in complex rhythms and extremely rapid tempos.

4. Hybrid Cyberinstruments and Cyberactions in *E-clip-sing* (2008)

My interest in growing orchids and my curiosity about their hybridization inspired *E-clip-sing* for amplified clarinet, guitar, cello, double bass and electronics. The composition fuses musical elements, instruments and performative actions, metaphorically referencing biological cross-breeding.

Hybridization is commonly considered artificial, but in nature orchids have proved that the genetic barriers between species may be much more fluid than we may think. Out of approximately 70,000 known orchid species less then half are the pure genera, such is the orchid's predisposition to adapt, fuse and transform whether in its natural habitat or domesticated environment. Perhaps this is due to the fact that unlike other species such as mammals, orchid cross-breeding, especially when involving closely-related classes, frequently leads to a "hybrid vigor" which signifies faster growth, longer bloom, vicissitude of cultivated life and other enhanced properties. A creation of flowers with unique colors, forms, shapes and smells drives the breeders to combine multitude of species from various geographical locations.

I created unique musical colors and forms with hybrid instruments, cyberinstruments and performative actions and cyberactions in *E-clip-sing.* Physical actions are embedded in the score which consists of graphical gestures mirroring the physical movement of the performers. In particular, I explored performance actions that are not native to the instruments, and by doing so, produced unique timbres. The electronic part engages hybrid cyberinstruments which combine parts of multiple parents in a single vibrating structure. Acting on the parallel, serial and network connections among the hybrid cyberinstruments signifies hybrid cyberactions. This 10-minute long composition is organized in three movements *Buiara*, *Psychopsis* and *Odontocidium,* named after three contrasting orchid hybrids.

4.1 *Buiara*

The first movement, *Buiara,* involves the string instruments, which are laid down flat on their backs. The performers use soft fabric or paper tissue to clean and polish the instruments, using circular, linear and other motions over various parts of the instrument's bodies, specifically their strings, bridges, frogs, pegs and metal holders (cello and double bass only). The performer may accidentally strike a string, but the main source of excitation for the resonant bodies is the subtle friction created between the paper and the various surfaces. Their precise control over the gestures and their timing results in delicate rhythmic patterns, and the resulting sounds are colored noises featuring the natural resonances of the instruments' bodies. The fast pacing of the material, tight synchronization and frequent performance mode changes make the music intense and exciting.

The sequences of actions are the thematic materials which are developed in *Buiara*. For example, such themes can be constructed as a slowly paced circular polish on the lower part of the body followed by three frantic sideways rubbing gestures of a single string behind the bridge and the up and down wiping of the bridge. All of the instruments present similar themes, their fragments and variations, resulting in a polyphonic action flow.

The computer functions as one voice in the polyphony with precise entrances and exits. I created the cyberhybrids in TASSMAN, a modular software synthesizer which enables the construction of modal synthesis-based physical models. Although the application can be used as stand-alone, it is most efficient when controlled via an external MIDI controller. I also used an M-Audio Axiom MIDI keyboard, to control various parameters of my cyberhybrids.

The electronics of the *Buiara* engage serially ordered virtual plectra exciting other plectra and mallets hitting other mallets, suggesting hybrid cyberinstruments. Performance actions such as plucking a plate with plectrum further accentuate the hybrid nature of the cyberinstruments. Implemented in various feedback loops, such mechanisms highlight the percussive portion of the performance action, effectively complementing the instrumental timbres. The following figure exemplifies two serially connected cyberhybrids in loops.

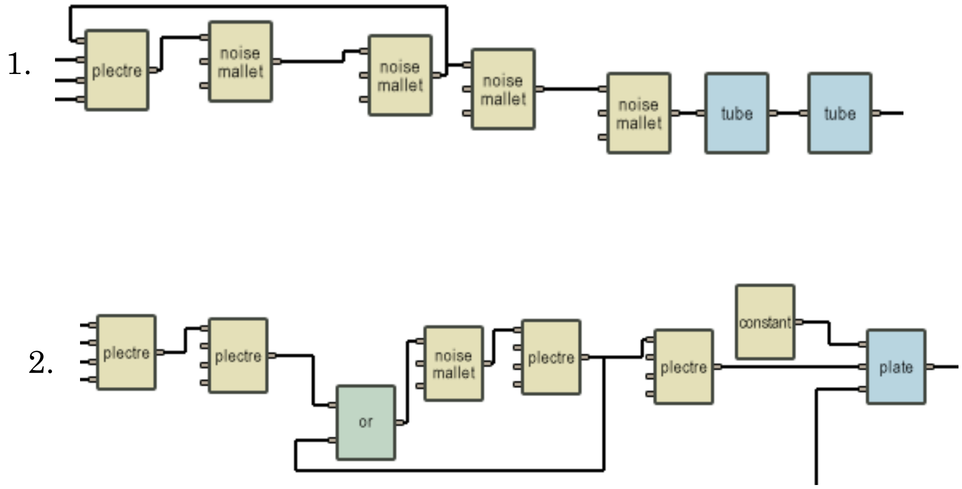

Figure 66. Two hybrid cyberinstruments emphasizing the excitation mechanisms of plucking and hitting.

4.2 *Psychopsis*

Psychopsis (the second movement) begins *attacca* with sustained clarinet tones which quickly turn into air tones while the string players fade out in thirty seconds using plastic straws to blow on and inside the instruments. The movement features solo clarinet and electronics. The disassembly of the physical clarinet is the main action explored in this movement. The soloist first plays the complete clarinet, then takes apart the instrument and uses the disaggregated pieces to produce unusual sounds. The poignant character of this movement is reflected in the sustained nature of the gestures in both the instrumental and computer parts.

The electronics here function primarily as the providers of a supporting layer. The cyberhybrids are designed with a single exciter (a plectrum) connected to multiple resonators in parallel in this movement. The hybrids gain in complexity as the outputs of individual parts are crossbred with additional parts, and a hybrid cyber-action results from plucking resonating structures such as beams, membranes and plates as shown in figure 67.

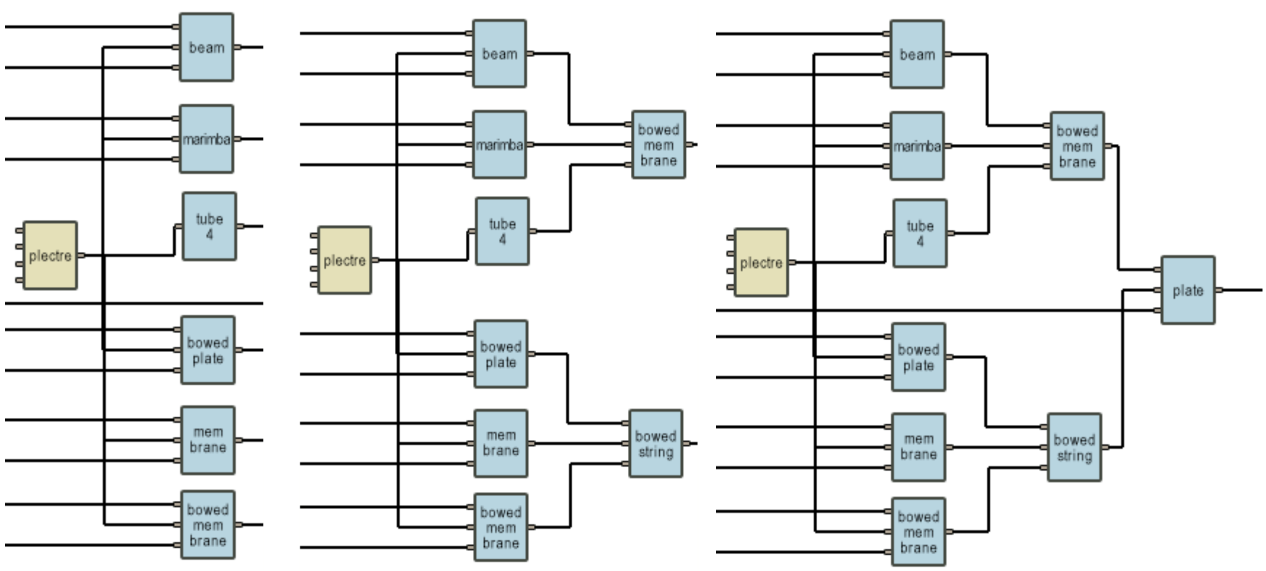

Figure 67. Three hybrid cyberinstruments connected in parallel. Note that the virtual plectrum plucks physically *unpluckable* elements.

4.3 *Odontocidium*

Movements one and two investigate a few selected performance modes, but *Odontocidium* (the third movement) engages numerous modes in a quasi "perpetuum mobile" motion. The string players utilize two rubber and yarn mallets each to excite the instruments by hitting, rolling and scraping them in various places, performing simple rhythms which when put together produce a complex polyrhythmic flow. They also rub the bows with plastic straws; pluck the bow hairs; and use traditional string exciters such as bows (I defined bows as instruments, which the performers bow with resined fingers creating intriguing friction sonorities) and plectra in unique ways, sometimes while striking the bow in various places with a mallet, the percussive vibrations adding a unique timbre to the bowed gestures. The plectra are also used as resonators while these are being hit and plucked by other plectra producing percussive sonorities.

To complement the various physical hybrid actions, the electronics in this last part of the composition present networks of exciters and resonators. Creating a metronomic pulse, they serve as a conducting force which leads the ensemble through this movement. Figure 68 exemplifies such a hybrid network. In it, a single mallet excites a cyberbeam, which then excites the cybermarimba and bowed cybermarimba and in turn controls the bow velocity of the bowed cyberstring. The cybermarimba also excites the mallet in a loop and controls the bow force of the cyberstring, while the bowed cybermarimba controls the damper signal of the beam. Once excited, this network continues resonating according to the alignment of its constituent parameters. In other words, changing a single parameter in any of the parts alters the behavior of the complete network. The virtual loudspeaker can be connected to any place within the network to hear the audio signal.

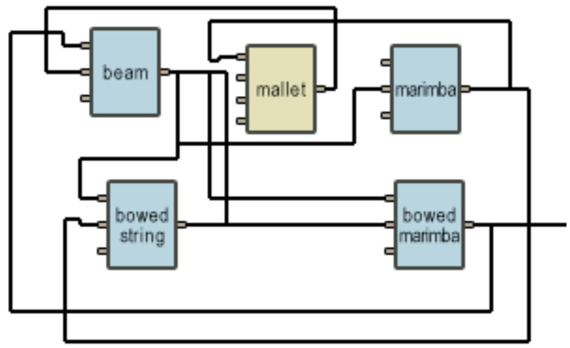

Figure 68. A cyberhybrid instrument in action. The various parts are connected in a closed network which one can listen to at any point.

In the short coda-like conclusion of *E-clip-sing*, the string players construct a resonating network of instruments in which the bridges of the string instruments are connected to each other with a wire. The clarinet player visits each instrument and blows on its bridge to excite the network and thus create subtle colored resonances of the instruments' bodies.

5. Abstract Cyberinstruments and Cyberactions in *At And Across* (2007)[22]

Like *Zvonenie, At and Across* investigates Slovak sheep bells. This composition, however, engages a physical performer and a set of physical sheep bells with an orchestra of cyberbells. *At and Across* also examines

[22] *At and Across* was first discussed in *At and Across: Physical and virtual action-based music* (Kojs 2007).

additional performance modes such as blowing, combines the cyberbells into a series of networks, and renders the melodic and harmonic trajectories more dynamic. Furthermore, it uses cyberbells not only in function of sounding instruments but also as cyberperformers and cyberconductors. Resulting abstract cyberactions signify transmutation of energies in a creation of unique musical behaviors.

5.1 Physical Bells

I acquired a sheep bell set from the bell-making master Julius Mikulas from Ilanovo, Slovakia. The eight custom handmade bells are tuned to the G mixolydian scale, which is the predominant melodic mode in Slovak folk music. The dominant resonant frequency of the bottom scale tone is G4 (784Hz), while the top note shows G5 (1568Hz) as its predominant resonance. The G4 bell is shown in figure 69.

The bells were made by hand from a single piece of brass alloy approximately 0.1 cm thick. The brass was folded and enclosed on its sides to form the bell's cavity, and the beater and handle later welded onto the bell's body. The size of the bell bodies suggests initial pitch consideration: larger bells produce lower fundamentals and vice versa. Hammering around the bell's rim is a technique used to refine and finalize the tuning.

A strong fundamental frequency and a small number of quickly decaying partials characterize the spectral behavior of this brass bell. A single hit on the bell's rim—the most resonant excitation place—produces a piercing attack sound which attenuates within approximately two seconds.

Material: Thin Brass	Total Height (TH)= 13cm	Wall Thickness (WT)= 0.1cm
Total Weight: 200g	Central Height (CH)= 10.3cm	Opening Width (OW)= 6cm
Beater Weight: 17g	Central Width (CW)= 10.5cm	Opening Height (OH)= 6.3cm

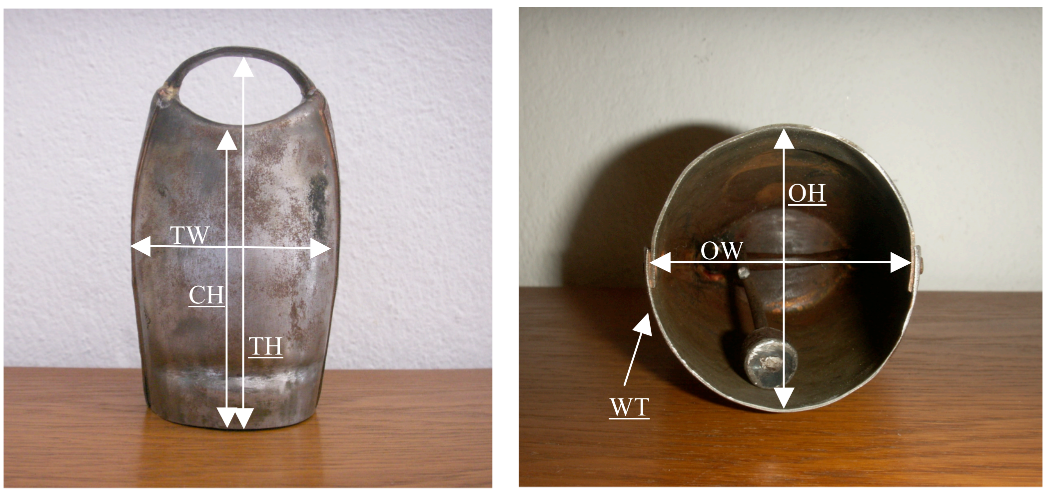

Figure 69. A light brass sheep bell designed by bell-maker Julius Mikulas of Ilanovo.

5.2 Cyberbell Design

I first designed the cyberbells to imitate the physical bells with a mass-spring-damper algorithm in GENESIS. The model consists of eleven masses of different weights which decrease symmetrically as they move away from the central point. These masses are connected with links of variable, and generally low, damping and viscosity values.

The cyberbell is replicated eleven times and tuned to eleven different fundamentals, which are related to each other according to the ratios proposed by J.C. Risset in his additive synthesis of a bell (Dodge 1997). The cyberbell proportions remain constant throughout the composition.

The cyberinstruments resonate as single units or they are connected into networks. The network links were designed to disturb the natural behavior of the resonating instruments, while avoiding the collapse of their internal structures. An example of such a network is presented below in figure 70.

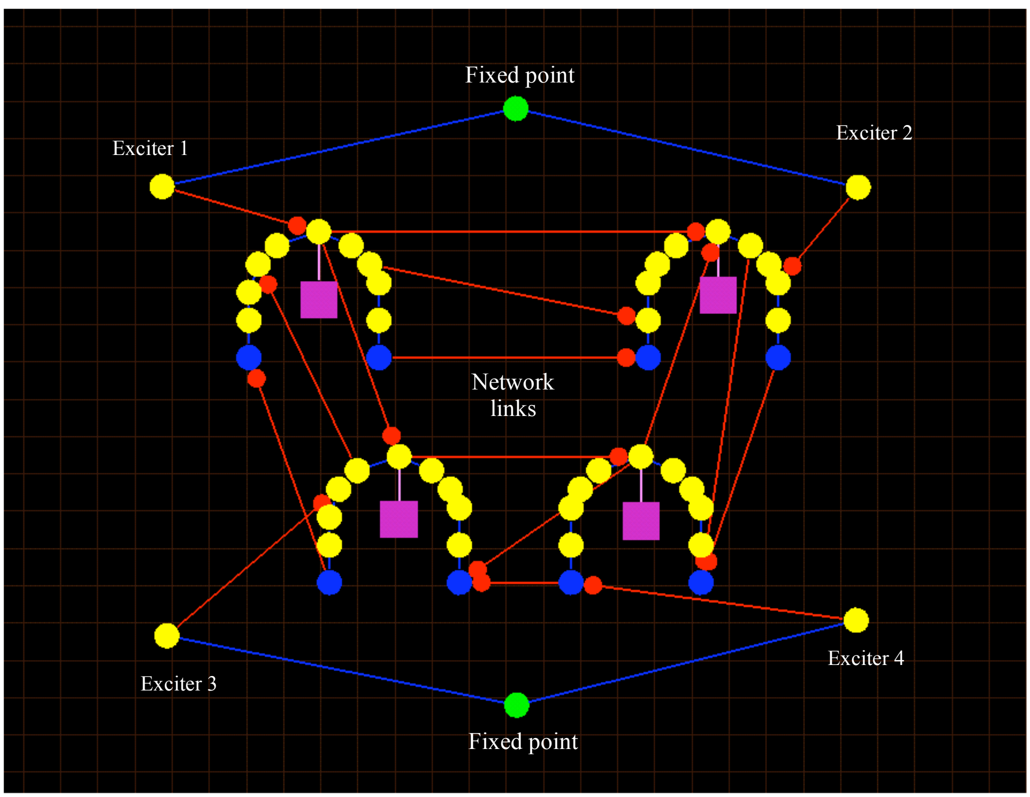

Figure 70. A network of four cyberbells hit by four exciters at different places.

I modeled the exciters as a combination of masses attached to fixed points and linear and non-linear links. Hitting, plucking, bowing and blowing mechanisms were used to excite the virtual bells. As an extension of what can be done in the physical world, the bells were exposed to unrealistic excitation situations. Multiple exciters of varying kinds acting on the same place of a single bell and single beaters and bows performing on multiple instruments exemplify such unusual excitations. Figure 71 shows a single exciter bowing the bell at eleven different places. Each bowing-link varied slightly in its parametrical design. Moreover, the positions of the virtual microphones were eventually altered while all other parameters were retained. The four virtual speakers scan the bell at four different places, suggesting a 4-channel audio “ear”.

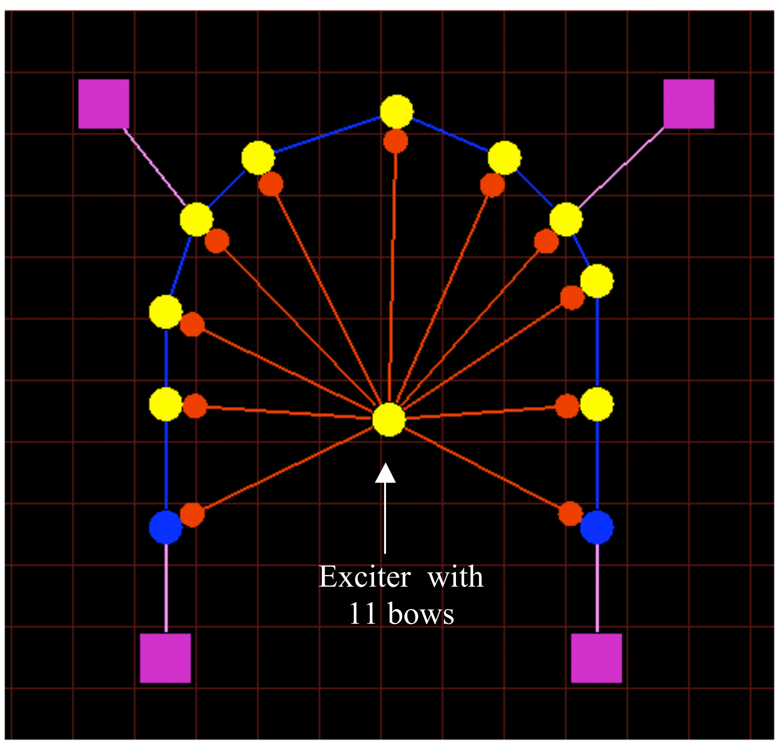

Figure 71. Single force bowing the cyberbell at eleven different spots.

GENESIS also enabled me to design abstract cyberactions and cyberinstruments. The design of the following such cybersintrument is based on the nesting of two cyberbells. While the bell comprising the instrument's outer layer is composed of denser materials, the middle cyberbell's structure is composed of thin springs with low stiffness. Behavioral collisions between these two layers create a vibrating abstract cyberstructure.

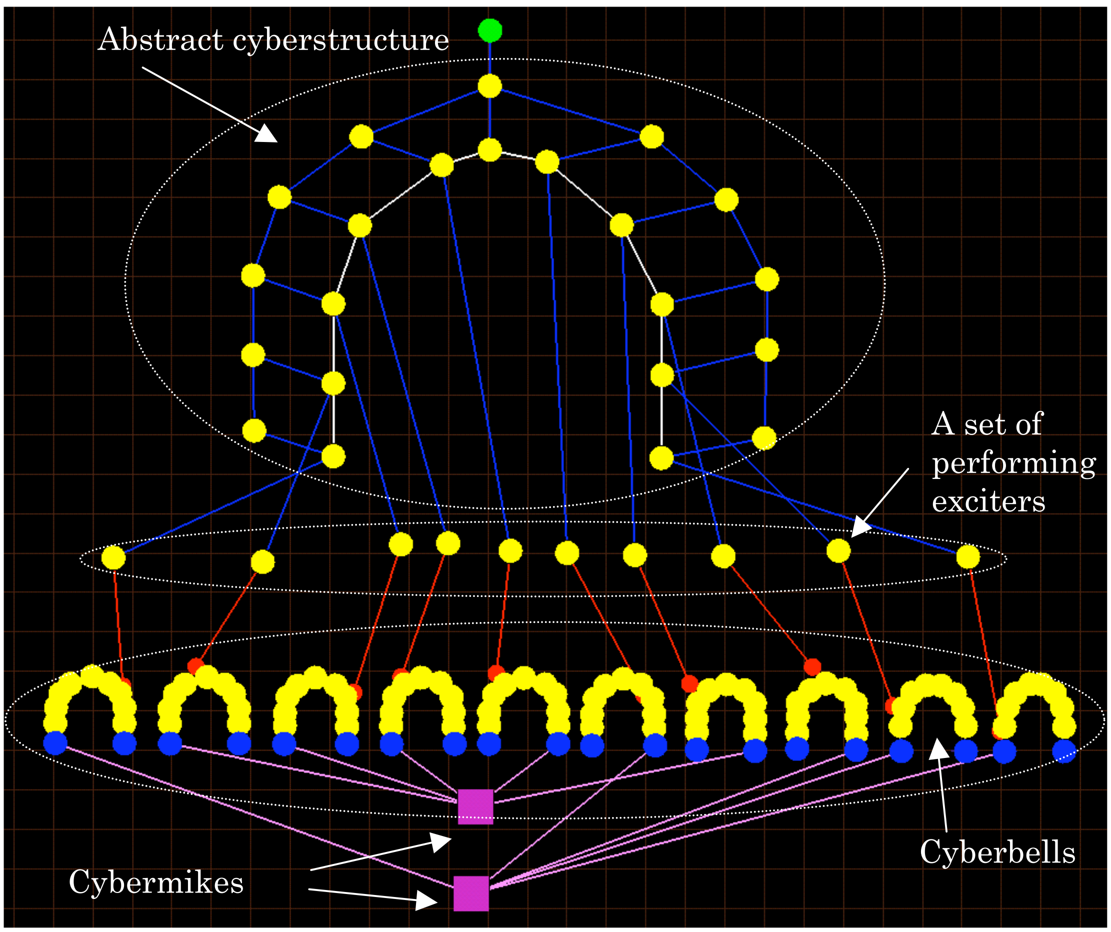

Figure 72. Abstract cyberstructure which movement directs eleven performing forces to act on 11 sounding cyberbells.

The resulting cyberstructure is further equipped with eleven arms which can excite the eleven sounding cyberbells in the bottom row. Note that although the abstract cyberstructure can propagate with motion, it never sounds. Its vibrational patterns are instead delivered to the beaters which excite the eleven cyberbells. The complete set-up is a type of conductor—performer—instrument virtual archetype.

5.3 Form

The interactions composed between the various cyberinstruments were exported as stereo and quadraphonic audio files to a digital studio, where they were assembled into a 4-channel soundtrack. The formal arrangement of both computer and acoustic parts follows the trajectory of hitting, bowing, blowing and plucking sequences.

The process of composing with actions proceeded as follows. First I investigated and catalogued the sound production mechanisms. These included (a) shaking, (b) hitting with metal, wooden and plastic beaters (mallet and stick parts), (c) bowing with the violin bow and (d) blowing inside the instrument. The performer conducted all of these actions while holding the instrument in the vertical and horizontal positions. I also hung the bells on a horizontal rod, which enabled controlled performance of multiple instruments. These actions were performed with and without partial or full muting.

After that, the individual actions became the primary framework for the component sections. The piece was composed as a sequence of actions with the following arrangement: *Intro, A, B, A', x', C, B', C', x", B", D, x'"*, in which A=hitting, B=bowing, C=shaking and D=combined modes. The performer holds all the bells in his/her hands and shakes them throughout the introduction. Lowercase *x* parts signify shorter solo electronics sections. Figure 73 shows the complete formal trajectory of *At and Across*.

Time	0—2'	2—3'30"	3'—5'	4'—5'30"	5'15" — 5'30"	5'30"—6'30"	6'30"—8'	8'—9'	8'30" —9'	9'—10'10"	10'10"—12'	11'—12'
Part	intro	A	B	A'	X'	C	B'	C'	X''	B''	D	X'''
Genesis		Hit single cyberbell	Bow	Hit cyberbell network	Poly-phony1	Hit multiple plate-like cyberbells	Bow, Blow cyberbell series	Hit single plate-like closed cyberbells	Poly-phony2	Blow, Pluck cyberbells	'Cyberbell' multiple cyberplates and cyberbells	Polyhonny3
Performer	Shake	Hand held (HH) + outside beaters	HH + Bow top	HH + inside beaters		HH + shake	HH + bow + bottom	HH + muted shake		HH + bow all and blow	HH + shake + suspended polyphony with beaters	

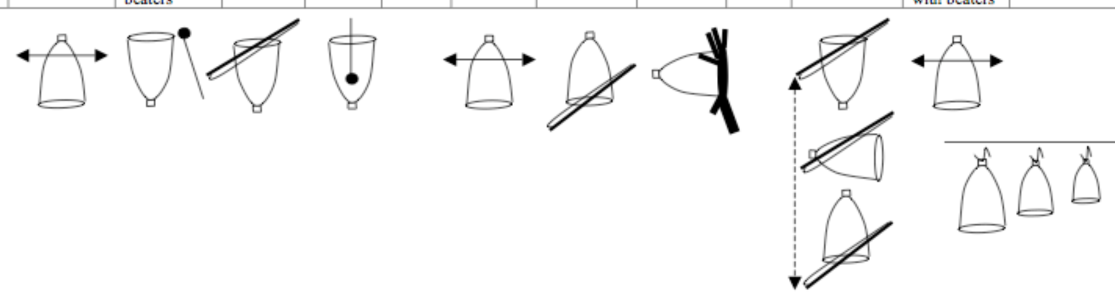

Figure 73. Complete formal design of *At and Across.*

I pre-composed the interactions between the physical and virtual bells according to melodic and harmonic plans. As the piece is dedicated to the memory of my grandfather, the composition's melodies are derived from his favorite Slovak folk song “Sadla muska na konarik” (“A little fly landed on a little twig”). Re-composed segments of the song appear in both the physical and cyberbell parts. Each section of the composition is built around a fragment from the song in both the physical and cyberbell parts. Depending on the performance mode and rhythmic complexity, these fragments may not necessarily be recognizable.

The harmonic and dynamic structures mirror and accentuate the spectral relationships between the partials of J.C. Risset’s additive synthesis bells. The quartic function—the inverse version of which can simulate the decaying behavior of a bell sound—is used as a formal agent for constituting the growing appearance of the cyberbells in the course of the piece as displayed in the figure 74.

While the background layer provided by the electronics flows with its own dynamics, the foreground is strictly structured to complement the physical performance. The complete electronics and acoustic signal join together in MAX/MSP where they are fed to resonant filters tuned to the partials of Risset’s bells. The sounds are also more dynamically spatialized using the group rotation algorithm similar to that of *Zvonenie*.

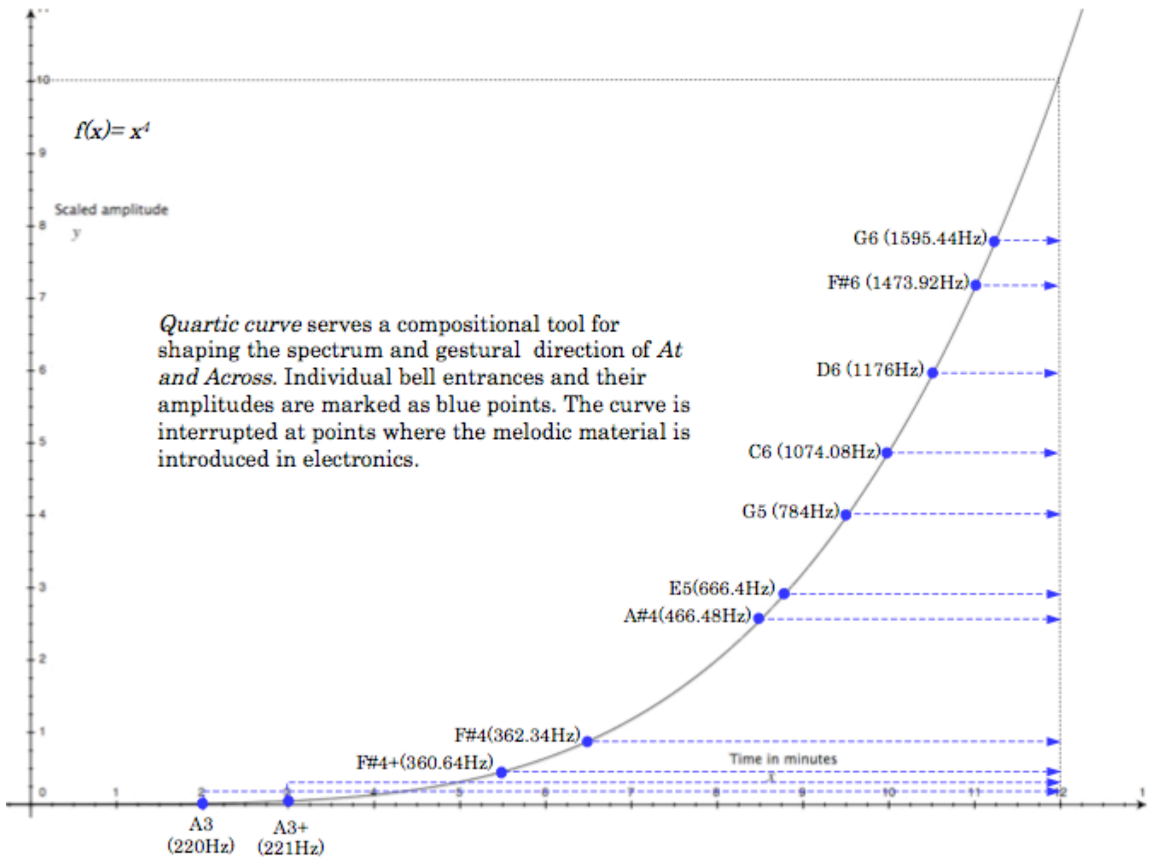

Figure 74. Quartic curve serves as a general structural guide in *At and Across*. Appearance of the individual cyberbells derived from Risset's series are reflected as point on the curve.

At and Across is an instance of action-based music composition. Such compositions highlight sound production as the primary tool for musical expression. Actions define the formal, instrumental, timbral and rhythmic areas of the composition. The cyberbells created with mass-spring-damper physical modeling approach enabled the transcending of the limitations of the physical world. Combining the physical sheep bells and virtual bell structures resulted in the creation of a unique augmented musical reality.

6. Conclusion

In this chapter, I discussed my compositions combining physical and virtual instruments. In them traditional instruments, Slovakian folk instruments and everyday objects interact with cyberinstruments designed using a variety of physical models. While most of the pieces investigate how cyberinstruments augment the timbral possibilities of their physical counterparts, in some cases a virtual instrument serves as resonant space (*In Secret, En Una Noche Oscura*) or reflective wall (*To Where He Waited*). *E-clip-sing* engages hybrids connected in series and in parallel and unique hybrid networks. *At and Across* presents abstract cyberstructures.

My music examines mechanical action as a primary expressive and structural tool. Actions are embedded in the scores too! In the physical world, the instruments often employ a variety of techniques which results in the creation of novel timbres. While timbre is the principal sonic parameter investigated in my works, pitch often shines through the colored noise. Together with time parameters such as rhythm and pacing, my pitch work is frequently derived from extra-musical sources such as text.

The physical models enable expanded timbres and actions in cyberspace. Plucking a bell and 'belling' a bell suggest extended and abstract cyberactions respectively. In several cases the cyberinstruments respond to gestures and signals provided by physical instruments in real-time. On occasion (*Neither Stirred Nor Shaken*), the actions are tracked with sensor technologies.

The process of combining physical and cyberactions suggests a smooth continuum between physical and virtual realities in music. The described compositions show how my sonic investigations developed from focusing on digital augmentation of the physical sources to the design of unique abstract structures and novel compositional methods. My music is intended to build a road for inquisitive expeditions to the virtual world. Achieving a greater understanding of and defining what virtual reality is makes this musical exploration exciting and most satisfactory.

CONCLUSION AND FUTURE DIRECTIONS

I have discussed the recent use of compositional applications of physical actions and their extension in cyberinstruments created by means of physical models. In the process, I defined an action-based music which enables thinking of music creation in terms of physical gestures and procedures in chapter one. In its purest form, instrumental design, composition and performance are created through various types of action, suggesting the incorporation of a choreography of gestures into the notation for such music. (I also detailed a topology of such actions for music composition.)

In chapter two, I suggested that physical modeling synthesis specifically is a suitable tool for the simulation of cyberactions and cyberinstruments in the digital domain. Rooted in mechanics, the physical modeling synthesis efficiently simulates sounding objects such as musical instruments and environmental phenomena.

In the third and final chapter, I described how my own compositions contribute to the current development of music written with cyberinstruments via physical modeling synthesis. In particular, I detailed how the extended, hybrid and abstract cyberinstruments enable a continuum between physical and virtual realities in my music. Such a continuum is constructed around the various interactions between the physical and cyberinstruments. The interactions are reflected in the formal organization and scoring of compositions, the design of software interfaces and even in the modeling process itself.

My future work will further develop the action-based global approach to composition in acoustic and virtual worlds. In particular, I will focus on creating and using abstract cyberinstruments and cyberactions. I will investigate what it means to make music with instruments that structurally transmute over time, a process with fascinating analogies to biological processes. The composer's operations with the internal 'cells' of an abstract cyberinstrument may be said to resemble the work of a genetic engineer. The models can exhibit organic processes such as growth and metamorphosis. Altering the interior properties of a virtual instrument revolutionizes the notion of what a musical instrument is, to say nothing of the compositional process.

They also have fascinating implications for sonic virtual reality and its relationship to physical reality, as discussed in Virtual Reality theory. For instance, according to the French cultural theorist Pierre Levy, the physical and the virtual are not in opposition. Rather, virtual reality complements and closely correlates with physical reality, expanding it. VR has the capacity to mirror, extend and transform the physical world (Levy 1998).

The process of virtualization (or becoming virtual) is suggested by the 'tool in action' metaphor. Levy recognizes two hierarchically ordered levels of virtualization: extension and abstraction. A tool may present itself simply as an extension of a human part, as when a hammer extends the hand. On a higher level, a tool may embody an abstraction of some human action. For example, a wheel constitutes a virtualization of walking.

I plan to investigate how cyberinstruments created via physical modeling furnish a connection to this tool–action paradigm. I will also continue to inquire into how the individual cyberinstrumental types complement the topology of virtual space. The investigation of perceptual issues connected to hearing in virtual space is also crucial, as is an effort to understand whether there exist common threshold limits between physical, extended and virtual sounds in aural perception, and how physical models capacitate expansions of our musical horizons. I will focus on studying how physical models capacitate expansions of our perceptual horizons.

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Appendix

Survey of compositions created with cyberinstruments via physical modeling synthesis

Name	Title	Year	Instrumen-tation	Cyberinstrument	Cyberinstrumental type as used in the composition	Physical modeling approach	Implemented environment and designer
Torsten Belschner	*Sono reMorphed*	2007	Audio-visual installation	Bowed string and blown pipe	Extended	1-D waveguides	16x Yamaha VL70-m
Torsten Belschner	*SonoMorphis*	1998	Audio-visual installation	Bowed string and blown pipe	Extended	1-D waveguides	16x Yamaha VL70-m
Achim Bornhoeft	*Virtual String*	1997	Stereophonic tape	Bowed string	Extended	1-D waveguide	
Matthew Burtner	*That Which is Bodiless Is Reflected in Bodies*	2004	8-channel tape	Tibetan Bowl	Extended	Banded waveguide	MAX/MSP; S. Serafin
Matthew Burtner	*S-Morphe-S*	2002	Metasaxophone and electronics	Tibetan Bowl	Extended	Banded waveguide	MAX/MSP; S. Serafin
Matthew Burtner	*S-Trance-S*	2001	Metasaxophone and electronics	Bowed string	Extended	1-D waveguide friction model	MAX/MSP; S. Serafin
Claude Cadoz	*Gaea*	2007	Quadraphonic tape	Percussive instruments and environmental phenomena, cyberperformers, cyberconductors, cyberform	Abstract	Mass-spring-damper Algorithm	GENESIS; C. Cadoz
Claude Cadoz	*pico..TERA*	2002	Quadraphonic tape	Variety of cyberstructures, cyberperformers, cyberconducters	Abstract	Mass-spring-damper Algorithm	GENESIS; C. Cadoz
Chris Chafe	*Score IV*	2007	Radio baton and electronics	Bugle, string, saxophone, human throat		1-D waveguides	C++; C. Chafe
Chris Chafe	*Tomato Quintet*	2007	Installation	Hydraulis, piano string		1-D waveguides	C++; C. Chafe
Chris Chafe	*Tomato Music*	2007	Computer generated sound	Hydraulis		1-D waveguides	C++; C. Chafe
Chris Chafe	*Scatter*	2006	Soprano and DVD	Plucked string		1-D waveguides	C++; C. Chafe
Chris Chafe	*Replication*	2005	Piano and DVD	Plucked string		1-D waveguides	C++; C. Chafe
Chris Chafe	*Replication*	2005	Piano and DVD	Plucked string		1-D waveguides	C++; C. Chafe

Chris Chafe	*Oxygen Flute*	2001	Installation	Chinese bamboo flute	Extended	1-D waveguides	C++; C. Chafe
Chris Chafe	*Ping*	2001	Internet installation	Plucked string	Extended	1-D waveguides	C++; C. Chafe
Chris Chafe	*Transect*	1999	Cello and electronics	Bowed cello	Extended	The McIntyre, Schumacher and Woodhouse Algorithm	C++; C. Chafe
Chris Chafe	*El Zorro*	1991	Trumpet and electronics	Bugle and brass	Extended	1-D waveguides	P. Cook
Ted Coffey	*Lullabies & Protest Songs: Suite No. 1*	2007	voice, guitar quintet, percussion, double bass, found and made instruments, live electronics, and live-mixed stereophonic tape	Glass harmonica		Banded waveguide	G. Essl
Ted Coffey	*No Further Meaning*	2007	shakuhachi, percussion, violin, recorded poet and live-mixed stereophonic tape	Glass harmonica		Banded waveguide	G. Essl
Ted Coffey	*Never Ate So Many Stars*	2006	stereophonic tape	Glass harmonica		Banded waveguide	G. Essl
Ted Coffey	*Armonica Lullabies No. 2*	2005	sound installation for quadrophonic tape	Glass harmonica		Banded waveguide	G. Essl
Ted Coffey	*Music for Lawn Games No. 3*	2005	outdoor sound installation for six parabolic reflective speakers and lawn games	Glass harmonica		Banded waveguide	G. Essl
Ted Coffey	*Nonlinear Ambient Music*	2005	live-mixed stereophonic tape and dancers	Blowtar: flute/electric guitar		1-D waveguide	MAX/MSP; D. Trueman
Ted Coffey	*Armonica Lullabies*	2004	stereophonic tape	Glass harmonica		Banded waveguide	G. Essl
Ted Coffey	*Untitled (Koans)*	2004	voice, alto saxophone, live-mixed stereophonic tape and animation	Glass harmonica		Banded waveguide	G. Essl
Ted Coffey	*Twice Twice*	2002	cimbalom and two times stereophonic tape	Percussion Bowed Bar		Banded waveguide	MAX/MSP-PerRColate; Georg Essl and Perry Cook

David A. Jaffe	*Racing Against Time*	2001	two violins, two saxophones, piano, Mathews Radio Drum, and live electronics	Car engine	Extended	Extended Karplus-Strong Algorithm Staccato Systems Car Engine Model	J. Smith and D. Jaffe; SynthCore; D. Jaffe imp. Tim Stilson, Sean Costello, et al.
David A. Jaffe	*Grass*	1987	vocalists and stereophonic tape	Bowed string	Extended	Bowed string synthesis based on modified version of Extended Karplus-Strong Algorithm	J. Smith and D. Jaffe; D. Jaffe imp.
David A. Jaffe	*The Fishing Trip*	1986	12 male vocalists and stereophonic tape	Plucked string Marimba		Extended Karplus-Strong Algorithm Modal synthesis	J. Smith and D. Jaffe; D. Jaffe imp. X. Serra
David A. Jaffe	*Telegram to the President*	1985	string quartet and electronics	Plucked string	Extended	Extended Karplus-Strong Algorithm	J. Smith and D. Jaffe; D. Jaffe imp.
David A. Jaffe	*Silicon Valley Breakdown*	1982	quadrophonic tape	Plucked string	Extended	Extended Karplus-Strong Algorithm	J. Smith and D. Jaffe; D. Jaffe imp.
David A. Jaffe	*May All Your Children Be Acrobats*	1980	mezzo-soprano, eight guitars, and stereophonic tape	Plucked string	Extended	Extended Karplus-Strong Algorithm	J. Smith and D. Jaffe; D. Jaffe imp.
Paul Lansky	*On F*	2006	Stereophonic tape	Clarinet, mandolin, and saxophone	Extended	1-D waveguides	STK; Models by P.Cook and G. Scavone; ported to SuperCollider3 by P. Lansky
Paul Lansky	*A Guy Walks into a Modal Bar*	2006	8-channel tape	Percussion bar	Extended	Modal synthesis	STK; Model by P.Cook and G. Scavone; ported to SuperCollider3 by P. Lansky
Paul Lansky	*Composition Project for*	2006	Stereophonic tape	Percussion bar	Extended	Modal synthesis	STK; Model by P.Cook and G.
Paul Lansky	*Composition Project for Seniors*	2006	Stereophonic tape	Percussion bar	Extended	Modal synthesis	STK; Model by P.Cook and G. Scavone; ported to SuperCollider3 by P. Lansky

Paul Lansky	*Things She Carried*	1997	Stereophonic tape	Plucked electric guitar	Extended	Extended Karplus-Strong Algorithm is	C. Sullivan
Paul Lansky	*Still Time*	1993-1994	Stereophonic tape	Flute	Extended	1-D waveguide	Ein; B. Garton, P. Cook, P. Lansky
Mauro Lanza	*Vesperbild*	2007	Ensemble, toy instruments and 5-channel tape	Percussions, whistles, strings	Extended and hybrid	Modal synthesis	MODALYS; M. Lanza
Mauro Lanza	*104*	2006	Stereophonic tape	Percussions, strings	Extended and hybrid	Modal synthesis	MODALYS; M. Lanza
Mauro Lanza	*I funerali dell'anarchico Passannante*	2005-2006	Choir and 14-channel tape			Modal synthesis 1-D waveguides	MODALYS; M. Lanza MAX/MSP: Percolate
Mauro Lanza	*Le Songe de Médée*	2004	Ensemble and 4-channel tape (music for ballet by A. Preljocaj)	Percussions	Extended and hybrid	Modal synthesis	MODALYS; M. Lanza
Mauro Lanza	*Mare*	2003-2004	Soprano, ensemble, toy instruments and stereo tape			Modal synthesis	MODALYS; M. Lanza
Mauro Lanza	*Burger Time ou les tentations de St Antoine*	2001-2002	Tuba and 8-channel tape	Percussions	Extended and hybrid	Modal synthesis	MODALYS; M. Lanza
Mauro Lanza	*Erba near che cresci segno nero tu vivi*	1999-2001	Soprano and 5-channel tape	Percussions	Extended and hybrid	Modal synthesis	MODALYS; M. Lanza
Michelangelo Lupone	*Canto di Madre*	1998	stereophonic tape	Bowed string	Extended	Hiller and Ruiz Algorithm	M. Palumbi and L. Seno
Michelangelo Lupone	*Corda di Metallo*	1997	string quartet and electronics	Bowed string	Extended	Hiller and Ruiz Algorithm	M. Palumbi and L. Seno
Max Matthews	*Bicycle Built for Two*	1960	Stereophonic tape	Vocal tract	Extended	J. Kelly and C. Lochbaum Algorithm	J. Kelly and C. Lochbaum
Max Matthews	*Bicycle Built for Two*	1960	Stereophonic tape	Vocal tract	Extended	J. Kelly and C. Lochbaum Algorithm	J. Kelly and C. Lochbaum

Juan Reyes	*Fuxing*	2006	multichannel tape	Bowed marimba and vibraphone	Extended	Banded waveguides	Common Lisp Music; J. Reyes
Juan Reyes	*Freddie the Friedlander*	2003-4	multichannel tape	Bowed and plucked string	Extended	1-D waveguide	Common Lisp Music; J. Reyes
Juan Reyes	*ppP*	2001	piano and electronics	Piano	Extended	1-D waveguide	Common Lisp Music; J. Reyes
Name	Title	Year composed	Instrumentation	Cyberinstrument	Cyberinstrumental type as used in the composition	Physical modeling approach	Implemented environment and designer
Juan Reyes	*Wadi Musa*	2001	quenas (Andean flutes), cello, and electronics	Maraca	Extended	PhISEM Approach	Common Lisp Music; Model by Perry Cook; J. Reyes extended
				Clarinet	Extended	1-D waveguide	STK; P.Cook and G. Scavone; J. Reyes extended
Juan Reyes	*Straw-berri*	1997	stereophonic tape	Flute and plucked string	Extended	1-D waveguides	STK; P.Cook and G. Scavone
Gary Scavone	*Air Study I*	2002	alto saxophone and stereophonic tape	Blown string	Hybrid	1-D waveguide	STK; G. Scavone
Dan Trueman	*Wind in Hands, Water in Feet*		Dance and electronics	Bamboo wind chimes	Extended	PhiSEM Algorithm	MAX/MSP; P. Cook
Dan Trueman	*Lobster Quadrille*	1999	Electronics via Bow-Sensor-Speaker-Array (BoSSA)	Shakers	Extended	PhiSEM Algorithm	MAX/MSP; P. Cook
Dan Trueman	*Improvisation*		Live improvisation	Blowtar: flute/electric guitar	Hybrid	1-D waveguide	MAX/MSP; D. Trueman
Hans Tutschku	*Resorption-Coupure*	2000	4-channel tape	Bowed and hit structures		Mass-spring-damper Algorithm	GENESIS; H. Tutschku
Hans Tutschku	*Eikasia*	1999	8-channel tape	Hybrid plates	Hybrid	Modal synthesis	MODALYS; H. Tutschku

A group of composers, such as Hans Peter Stubbe, Ludger Bruemmer, Giuseppe Gavazza, Periklis Douvitsas and Frederic Curien, have composed music with GENESIS at the Association pour la Creation et la Recherche sur le Outils d'Expression (ACROE) center in Grenoble, France. Some composers created concert works using the extended, hybrid and abstract cyberinstruments (Stubbe). Others have constructed multimedia (Bruemmer and Gavazza) and theatrical works (Douvitsas) with GENESIS.

Cyberactions and Cyberinstruments via Physical Modeling Synthesis:
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