Expressive Digital Musical Instruments for Children

by

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Submitted to the Program of Media Arts and Sciences, School of Architecture and Planning
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Abstract

This thesis proposes to use technology to introduce children to musical expressivity and creativity. It describes a set of digital musical instruments that were developed in an effort to provide children with new tools for interaction, exploration and enjoyment of music. The thesis unfolds a multidisciplinary theoretical background, which reviews a number of philosophical, psychological, musical, and technological theories. The theoretical background focuses on enlightening a number of personal musical experiences and leads towards the formulation of three musical concepts that inform the design of the digital musical instruments. The musical concepts are: High and Low-level Musical Control, Immersive and Constructive Musical Experiences and Interdependent Group Playing. The thesis presents the embodiment of these concepts in digital musical instruments while emphasizing the importance of novel technology as a provider of creative and expressive musical experiences for children.

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1 THEORETICAL BACKGROUND

1.1 Music Cognition

In this section I present the philosophical and psychological background for my research. I discuss different views of music as a symbolic system, present the notions of low and high-level musical conceptualization, and review relevant cognitive experiments. A special emphasis is put in this section on building a theoretical framework, which will illuminate a set of personal musical experiences (described in chapter 2) as transitional processes that encourage musical expressivity and creativity. Hence, the section does not serve as a general literature review; rather it builds towards the formalization of the musical concepts that inform the design of the digital musical instrument.

1.1.1 Musical Expression

Early Greek thinkers were probably the first to formulate a direct relation between musical modes and different human traits and emotions. Socrates for example, associated the Ionian and Lydian modes with indolence and softness and the Dorian and Phrygian modes with courage and determination [Plato, Saunders (ed) 1987]. Later composers and musicologists found interest in formulating similar connections. Early 20th-century Russian composer Aleksander Scriabin's theory correlated between notes, colors and emotions [Bowers 1996]. Psychoacoustics researchers like Herman Helmholtz have elaborated on this idea by trying to provide an experimental background for analyzing different tones and intervals in regard to their emotional effect. In *On the Sensations of Tone* [1954] Helmholtz argues: "melodic passages with the Pythagorean thirds have a strained and restless effect, while the just thirds make the same passages quiet and soft" [pp. 407-408]. This line of thought was continued during the last few decades with scholars like neuroscientist and musician Manfred Clynes, who in 1989 presented the *Sentic* theory [Clynes 1989], where he correlated emotions, musical components and brain activity.

Such literal theories have always been criticized by scholars and musicians who do not believe in simple connections between air pressure signals and complex human emotions. Igor Stravinsky in his famous remark argued, "Music is powerless to express anything" [Craft 1971 p. 29]. He later corrected himself, affiliating musical expression with the subjective composer's emotional world: "Today I would put it the other way around. Music expresses itself....A composer works in the embodiment of his feelings and, of course, it may be considered as expressing or symbolizing them" [p. 32]. Other scholars tried to ignore altogether the affective realm, constructing their musical theories on cognitive and mathematical terms. Musicologist Heinrich Schenker based his musical analysis on the notion that at a deep perceptual level, western music is based on one fundamental musical structure [Laskowski 1986]. As a result, Schenkerian analysis can reduce many western musical masterpieces to one big elaboration on a basic chord progression pattern. Composer Arnold Schoenberg, on the other hand, based his Dodecaphony musical theory on mathematical permutations of twelve-tone sequences, defying the expressive and affective musical vocabulary that was developed in the Romantic period.

When comparing the affective approaches with the analytical ones, one cannot ignore the fact that it is easier to address music with rationalist concepts such as pitch, rhythm, timbre and form, than it is to address the expressive nature of abstract musical symbolism. Psychologist Howard Gardner recognizes these facts and goes on to say:

> *Yet hardly anyone who has been intimately associated with music can forbear to mention its emotional implications: the effects it has upon individuals, the sometimes deliberate attempts by composers (or performers) to mimic or communicate certain emotions; or, to put it in its most sophisticated terms, the claim that, if music does not in itself convey emotions or affects, it captures the forms of these feelings." [Gardner 1983, pp. 105 –106]*

1.1.2 Discursive and Presentational Symbolism

The importance of symbols in our perception of the world was studied by some of the greatest scholars of the 20th-century including Freud, Jung, Levi-Strauss and others. One of the first efforts to describe a well-organized, coherent symbolic system for the Arts was done by Nelson Goodman [1976]. However, Goodman does not elaborate on the musical symbolic system, but mainly discusses the symbolic nature of musical notation. Philosopher Susan Langer [1942], approached the challenge of explaining the symbolism of artistic expression by defining two different symbolic systems – the "Discursive-Linguistic" and the "Presentational-Artistic." Langer claims that due to its serial nature, the discursive-linguistic symbolic system is a poor medium for communication of expressions. This system can hardly describe the common human cognitive state of multiple, sometimes contradicting, ideas or thoughts. Similarly to other philosophers (such as Cassirer, Delacroix and Whitehead) who claimed that the field of semantics is wider than the field of language, Langer articulates the deficiencies of language as an expressive medium:

> *It [language] merely names certain vaguely and crudely conceived states, but fails miserably in any attempt to convey the ever-moving patterns, the ambivalence and intricacies of inner experience, the interplay of feelings with thoughts and impressions, memories and echoes of memories, transient fantasy, or its mere runic traces, all tuned into nameless, emotion stuff [p.100].... there is an unexplored possibility of genuine semantics beyond the limits of discursive language" [p. 86].*

As a complementary semantic system Langer suggests what she defines as a "Presentational Symbolic System," which provides a medium for artistic expression, which is characteristically conceived as "inexpressible". In particular Langer refers to visual forms like painting, which do not present their constituents successively, but simultaneously. As she points out: "An idea that contains too many minute yet closely related parts, too many relations within relations, cannot be 'projected' in discursive forms; it is too subtle for speech" [p. 93].

By trying to apply Langer's vocabulary to music, one can identify the multi-faceted nature of the musical medium. Music is an artistic, presentational medium that propagates discursively in time. Hence, music should be able to involve an interaction between presentational and discursive symbols. According to this theory, the discursive analysis of the musical experience can be related to a "bottom-up" approach, where basic building blocks are grammatically constructed in an effort to create meaning. In the same way, the presentational nature of music can be related to a "top-down" approach, which involves an immersive, holistic experience that may, or may not, be broken down into its components.

These two symbolic systems are going to play an important role in the musical instruments that I describe in this thesis. With these instruments I try to provide a medium for children (who are not necessarily familiar with music theory or performance) to express themselves in a meaningful artistic manner. These instruments will embody both the discursive and presentational symbolic systems, while a special emphasis will be put on the transitional process between those two approaches.

1.1.3 Cognitive experiments

Bottom-up analytical approaches and top-down experiential ones also inform cognitive researchers like Deutsch [1981], Lockhead et al. [1981] and Shepard [1982] in their musical perception studies. The bottom-up cognitive experiments focus on how subjects process isolated musical components, devoid of a large musical context. In these studies, subjects are asked to indicate which of two notes is higher or louder, whether two rhythmical patterns are the same, etc. Due to their isolated nature, these experiments are easy to perform and are favored by empirical researchers. However, the relevance of these experiments to what we see as "a full musical experience" is doubtful. Many musicians are skeptical as to the possibility of building up to an analysis of a broad contextual musical experience based on such small-scale perceptual components. Top-down experimenters who try to address these deficiencies presented subjects with full musical pieces and investigated their response to experiential musical properties. Subjects are asked questions like: Does the music get slower or faster, softer or louder? Is the musical piece heavy or light, triumphant or tragic, crowded or sparse? While more appealing to musicians, this method fails to provide appropriate control and is incapable of objective analysis due to the subjective terminology it employs.

The difficulties in both approaches lead researchers like musician and cognitive scientist Carol Krumhansl [1979] to look for "middle ground" approaches using musical entities that are large enough to be perceived as musical, yet sufficiently susceptible to analysis to permit a systematic experimentation. In these experiments subjects were presented with tasks like choosing an appropriate ending to pieces in different keys, grouping varied rhythmical patterns, appreciating the privileged relationship between the dominant, subdominant and tonic, gesturing a melody contour, realizing the proximity of different scales, expecting leading tones, resting tones and cadences, etc. While providing a more accurate and controllable musical ground, this approach tends to miss important aspects of the holistic high-level musical experience as well as the constructive low-level one. The approach is also highly culturally biased and applies mostly to the music of western culture.

1.1.4 Cultural and Generic Symbols

Different musical characteristics arouse different connotations in different cultures. For example, in western music "death" is commonly depicted by slow tempi and low ranges. In African tribes it is portrayed in frenzied musical activity [Nettle 1956]. Different instruments in different cultures symbolize different concepts and states of minds. The gong in western music is almost always affiliated with the orient and often connotes the mysterious and the exotic, while in Asian music it usually bears inner-medium functionality, such as dramatic accentuation or timbral emphasis. Certain tonalities (like pentatonic scale, which in the 19th century was affiliated with pastoral mode), or intervals (like the diminished fifth, which was closely associated with grief and anguish during the baroque) bear different symbolic representations in different cultures at different times. Leonard Meyer in *Emotion and Meaning in Music* [1956] argues:

> *Notice that all these associations are intracultural....In western music, for example, the harp is no longer associated, as it was in the Middle Ages, with religious subjects. Because of its use in French music of the late nineteenth century, it is much more likely to be associated with a certain tender vagueness.... [p. 259]*

Meyer then suggests a different symbolic system, which is based on global common experiences and stimuli. He emphasizes the connection between musical symbols and natural human activity and suggests that both music and life are experienced as dynamic processes of growth and decay, activity and rest, tension and release:

> *If connotations are to be aroused at all, there will be a tendency to associate the musical motion in question with a referential concept or image that is felt to exhibit a similar quality of motion ... a motion may be fast or slow, calm or violent, continuous or sporadic, precisely articulated or vague in outline. [261]*

I believe that young children worldwide can relate to generic "motion-based" musical symbols. Some of the algorithms that I designed address these inter-cultural representation symbols. For example, I hope to show how algorithmic controllers for musical "stability" or "contour" can allow children of different ages and origins to communicate their musical ideas in an intuitive way. The particular cultural associations that these symbols may also embody can serve as an enriching added value for different players in different cultures.

1.2 Learning Music

In this section I discuss theories of learning in general, and learning music in particular. I present several musical education methods and discuss the tension between "Musical Intelligence" [Gardner 1983] and musical training. I end the section by suggesting that digital musical instruments can bridge the learning gap between the figural and the formal musical modes.

1.2.1 Society of Mind

In *Society of Mind* [Minsky 1985] Marvin Minsky argues that human personality is not controlled by a centralized "conductor" in the brain, but rather emerges from seemingly unintelligent and unconnected mental processes, or "agents." Minsky describes complex processes such as learning by a socialization mechanism of simple agents and agencies. For example, all that a "Polyneme" agent does is send the same simple signal to many different agencies. Minsky uses the Polyneme "apple" as an example: "It knows nothing whatever about apples, colors, shapes, or anything else. It is merely a switch that turns on processes in other agencies, each of which have learned to respond in its own way" [p. 198]. The "Paranome" agent serves as an important part of the learning process by being able to operate on agencies of several different mental realms at once. This can be helpful for learning new multiple meanings for things in the world, as the Paranom agent serves as a negotiator among the different conceptual realms. According to Minsky, different stages of development can also be portrayed as simple agents:

> *Each new stage first works under the guidance of a previous stage, to acquire some knowledge, values and goals. Then it proceeds to change its role and becomes a teacher to subsequent stages....How could an early stage teach anything to a later one when it knows less than its student does?...A teacher need not know how to solve a problem to be able to reward a student for doing so or to help the student search for solutions by imparting ways to sense when progress has been made. [p. 174]"*

1.2.2 Musical Intelligence

Psychologist Howard Gardner also believes in innate mechanisms and tendencies as the basis for learning processes in general and learning music in particular. In *Frames of Mind* [1983] he argues that of all the gifts with which individuals may be endowed, none emerges earlier than musical talent. Gardner refers to this musical talent as part of what he defines as "Musical Intelligence" – a separate musical entity in a full range of non-related "Multiple Intelligences" (linguistic, logical, interpersonal and others). Gardner, however, *does* recognize the importance of culture and training in Musical Intelligence:

> *The existence of accomplished singing skill in certain cultural groups (Hungarians influenced by the Kodaly method, or members of the Anang tribe in Nigeria) and of comparable high quality instrumental performances among Russian Jewish violinists and Balinese gamelon players suggest that musical achievement is not strictly a reflection of inborn ability but is susceptible to cultural stimulation and training. [Gardner 1983, p. 112]*

Gardner et al. [Davidson 1981] take an observational approach for studying the music learning processes. For example, They describes the development of the singing competence and claims that during infancy normal children can emit individual sounds, produce undulating patterns, and even imitate prosodic patterns and tones sung by others. In the middle of the second year children begin to emit series of punctuating tones that explore various small intervals: seconds, minor thirds, major thirds, and fourths. For a year or so, there exists a tension between the invention of spontaneous songs on the one hand and the production of "characteristic bits" from familiar tunes on the other. By the age of three or four, the melodies of the dominant culture have usually won out, and the production of spontaneous songs and sounds generally wanes. By school age, most children can produce a reasonably accurate facsimile of tunes commonly heard around them. It is important to note that there are striking individual differences in young children's musical competence. For example some children can sing large segments of a song by the age of two or three, whereas many others may still have difficulty in producing accurate melodic contours at the age of five or six. According to Gardner, in our culture there is little further "musical intelligence" development after school years begin. There is only an increase in knowledge about music, as many individual become able to read, analyze and play music.

One of Gardner's most interesting observations suggests that infants in our culture present enhanced creativity in terms of "composing" their own melodies in comparison with 3 and 4-year-olds, who tend to reproduce the existing music of their culture. It is also clear that this process is not easily reversed and that many will find it difficult to return to composing their own melodies ever after. This leads to the concern that children might lose their innate ability to compose due to environmental influence. In the "Personal Motivation" section I will show how my own composition skills were initiated after an interaction with a broken musical toy. I will later suggest that by interacting with the digital musical instruments that I design, infants and toddlers will also be able to create and experiment with their own music. This will hopefully contribute to the preservation of children's natural creativity and composition skills.

1.2.3 Music Education Methods

Current music education methods focus on different aspects of early musical development. The Orff Schulwerk method, for example, focuses on the traditional music and folklore of each country in which it is used, by utilizing things children like to do: "sing, chant rhymes, clap, dance, and keep a beat on anything near at hand" [Warner 1991]. The system tries to educate for musicianship and artistry by making music first, then reading and writing it later. Orff Schulwerk uses poems, rhymes, games, songs, and dances as examples and basic materials. Similarly to the Orff method, the Dalcroze Eurhythmics approach also focuses on gaining a practical experience of music before theorization. The method is based on a holistic premise that the "human body is the source of all musical ideas" [Dalcroze 1999]. The emphasis on physical and kinesthetic awareness is aimed at providing a concrete approach through movement to the abstract medium of music. Like Meyer, the Dalcroze Eurythmics emphasizes the idea that "Movement is a universal and fundamental human experience. If its impact in everyday situations is the creative well-spring of the composer, then human movement is the point of entry to the deepest level of musical comprehension" [Dalcroze 1999]. The Dalcroze method tries to implement this idea in three main realms: Rhythmics, Solfège, and Improvisation.

Although the Orff Schulwerk and the Dalcroze Eurythmics methods systems seem to be enjoyable and fun for children, both suffer from a number of substantial shortcomings. By limiting themselves to the experiential-presentational mode, these methods tend to neglect deeper levels of the musical experience. As the Dalcroze Eurythmics pamphlet claims, the system limits itself to "the point of entry to the deepest level of musical comprehension" and does not attempt to go further. This is particularly problematic as children mature and start to look for more comprehensive internalization of musical theory. Another weakness in both methods is their limited use of musical instruments. As I will show later, interacting with physical instruments serves an important role in enhancing any educational experience. These methods, however, do not attempt to emphasize instrumental activities, and usually restrict themselves to utilizing percussive objects as extensions to other body activities.

One educational system that *does* center on an instrumental approach is the Japanese Suzuki training method [Suzuki 1969]. The system has shown that a large number of individuals can learn to play musical instruments remarkably well, even at early ages. The method is based on concepts like parent involvement, early beginning, learning with other children and graded repertoire. However, the Suzuki approach demands a long technical learning process, which shadows the expressive and creative nature of music. This may explain why the method is not especially successful in producing great concert-player musicians, which are skillful and expressive. Despite these deficiencies, the large number of "Suzuki Youngsters" who accomplish impressive musical skills indicates that such musical fluency is achievable for not only unusually gifted individuals. This serves as an encouraging testimony to the potential that is embodied in allowing a wide range of children to be introduced to music by expressive digital musical instruments.

1.2.4 Figural and Formal learning

A common problem in many of the popular music education methods is how to deal with adolescence, when many children stop pursuing their musical practice. Jeanne Bamberger provides an insight into the reasons for this pedagogical problem. Bamberger [1982] claims that children up to around 12 years old are inclined to process music in a "Figural Mode." In this mode, children are encouraged to focus on intuitive aspects of music like the global features of melodic fragment, the "felt" features of contour, rhythm and grouping, etc. This "know-how" approach is based on intuition and creation, irrespective of any theoretical knowledge about music. Around the age of pre-adolescence many education methods tend to abruptly expect children to process music in what Bamberbger defines as the "Formal Mode" where musical notation, theory and analysis enhance the musical experience. As part of this "know-that" approach, certain important musical aspects that came naturally in the figural mode may be hidden, at least temporarily, when children are trying to superimpose prepositional knowledge upon figural intuitions. If this "crisis" is not acknowledged and the gap between the different modes is not negotiated, it might ultimately lead children to cease altogether their participation in musical life.

The Figural/Formal differentiation bears a resemblance to Langer's presentational and discursive symbolic systems polarity. The expressionist nature of the figural mode is compatible with the holistic nature of the Presentational symbolic system. The Formal mode on the other hand can be associated with discursive symbolic systems. Since digital instruments can be reconfigured, fine-tuned and personalized, they can provide an open-end continuum for different children to experiment in these different modes. I will describe the two polarities of this continuum as "immersive" and "constructive" musical experiences, and will describe my effort to implement them in the musical instruments that I design.

1.3 Interaction with Objects

In this section I discuss the importance of interacting with physical objects in children's cognitive developmental process and present the educational and psychological value of enhancing these objects with digital technology. I end the section by suggesting that digital musical instruments can make an important contribution to children's musical experience by projecting new meanings onto notions like musical expressivity and creativity.

1.3.1 Interaction with Physical Objects

Children construct an important part of their knowledge about the world by interacting with physical objects. Freud [1983] related the importance of objects in the human experience to their ability to "embody problematic needs, feeling or ideas." Winnicot [1971] presented the important role of what he defined as "transitional objects" to children's emotional development. Such "not-me possessions" (like a blanket to which the infant is attached) serve an important role in the differentiation between the subject and the physical world. Piaget on the other hand [1972] focused on the vitality of interacting with objects to the human cognitive development processes: from spatial locomotion and definition of the self, to symbolization, representation and other high-level processes, all are greatly constructed and enhanced by interacting with physical objects. One example brought by Piaget is the contribution of interacting with objects to the formulation of notions like "space", "object" and the "self" during the sensory-motor stage:

> *"The Object thus acquires a certain spatio-temporal permanence, and this gives rise to the specialization and objectification of the casual relations themselves. Such a differentiation of subject and objects....leads the subject to consider his own body as one object among others.... [Piaget 1972, p. 22]*

Mihaly Csikszentmihalyi and Eugene Rochberg-Halton further developed Piaget's studies. In "The meaning of things" [1981] they provide an empirical analysis of the interaction between people and objects by emphasizing man-made objects, where analysis of the creator's intention is as important as the user's side of the study. Csikszentmihalyi and Rochberg-Halton relate the importance of interacting with objects to the "Triadic nature of meaning: When we interpret a thing it acts as a sign (first element), standing for something (second element), through creating an interpreting thought or emotion (third element). The new sign, created through the interpretation may be equivalent to the first sign or may be more developed" [p. 50].

Various studies have also shown the importance of *playing*, as one of the most powerful modes of interaction with objects, for children's development. Researchers in the Harvard Project Zero [Shotwell 1979] have shown how "dramatist" and "patternist" behaviors evolve from corresponding play patterns with blocks. "Patternist" children focused on using the blocks to create structures and patterns in an analytical way while "dramatists" used them for creative theatrical role-playing. Those play patterns were shown at different cognitive development stages and were intensified by the interaction with the physical objects. Singer [1994] has elaborated on this matter by showing how imagination and creativity evolve from "fantasy play" with objects. He demonstrates how children's creativity is enhanced by "imaginative play" with neutral objects, when children use their imagination to create role-playing scenarios. Almquist [1994] has elaborated on "educational and creative toys" and emphasized the fun aspect of playing with toys as a motivation for children to learn. She exemplifies how having fun can serve as an efficient way to be immersed in the new material and absorb it, without necessarily being consciously aware of the process. This notion led me to formulate the idea of "Composing through Playing." The rationale here is to provide children with fun activities that they consider as "play" and would therefore engage in them from within. While immersed in these activities affectively, the musical value does not have to appear straightforwardly. By gradually discovering the musical consequences of their motions, children can navigate their gestures into musical domains and internalize musical concepts.

1.3.2 Interacting with Digitally Enhanced Objects

Symour Papert was one of the first to study how embedding technology in objects can enhance children's learning. In Mindstorms [1980] he describes how his personal interaction with differential gears at the age of two enhanced his mathematical thinking and abilities as an adult. He relates this enchantment to Piaget's notion of assimilation and extends this notion by presenting the *affective* aspects of the assimilation in addition to Piaget's *cognitive* emphasis. Researchers in MIT's Media Laboratory elaborated on Papert's ideas and embedded technology in physical objects in order to enhance children's and adults' everyday experiences. Hiroshi Ishii and Brygg Ullmer [1997] presented the notion of Tangible Bits: Graspable digital objects whose goal is "to bridge the gaps between both cyberspace and the physical environment." For example, they have developed the "phicons" (physical icons) that allow physical manipulation of a digital map. While allowing for digitally enhanced editing and manipulation functions, the phicons can also provide users with a better spatial understanding of the landscape.

Mitchel Resnick et al. [1996] focused on developing digital toys in an effort to enhance children's learning activities. This effort is informed by the notion of "Designing for Designers" – the belief that a toy will encourage creative exploration if the toy's designer considers children as collaborators in the design process and not just as "final users." Resnick presents a musical example to demonstrate his philosophy:

> *The Stereo has many attractions: It is easier than the piano to play, and it provides immediate access to a wide range of music. But "ease of use" should not be the only criterion. Playing the piano can be a much richer experience. By learning to play the piano, you can become a creator, not just a consumer of music, expressing yourself musically in increasingly*

> *ever-more complex ways. As a result, you can develop a much deeper relationship with (and deeper understanding of) music. [p. 41]*

The "Programmable Brick," developed by Resnick et al. demonstrates how technology can enhance children's learning. The brick is a tiny computer embedded inside a Lego© construction block. Unlike traditional construction kits' blocks that enable children to build structures and mechanisms, the programmable brick adds a new level of construction by enabling children to create behaviors for the objects that they build. The "Cricket" (the newest member of the programmable brick family [Martin 1998]) can control two motors and receive information from two sensors. Crickets are equipped with an infrared communication system that allows them to communicate with each other. Children can write LOGO [1999] programs on the computer and download them to cricket-based objects that they construct. By designing behaviors for these objects, children can experiment with the physical embodiment of their programs. A similar notion of enhancing familiar objects with technology in a way that can allow children to experiment and interact in new ways informs the design of my musical instruments. For example, I have formulated the concept of "Interdependent Musical Interactions". This concept employs different communication technologies in order to allow players to influence and control other players' musical output.

1.3.3 The Second Self

Sherry Turkle [1984, 1995] has studied how interaction with computers and digital objects enters into children's social life and psychological development. She demonstrated how computers can affect the way children think about the world and especially about themselves. For example, Turkle describes how playing with a digital interactive toy, like Merlin, can challenge the boundaries of notions like "self" and "life." Children who reflected on the experience of playing with the toy were able to formulate interesting views as to whether Marlin is "alive," like themselves, or not. Hence, the interaction with the digital toy led players to contemplate deep philosophical issues such as framing sufficient and obligatory definition for the concept of life – a deep and challenging task for children at the age of seven.

Turkle and Papert [1992] also expanded Levi-Straus's idea of "bricolage" to describe different ways of interaction with computers. They associate the bricolage approach with concrete, close-to-the-objects experience and the opposed "planners approach" with abstract, hierarchical and axiomatic thinking. Turkle and Papert explain:

> *Bricoleurs use a mastery built up through associations and interactions. For planners, mistakes are missteps; bricoleurs navigate through mid-course corrections. For planners, a program is an instrument for premeditated control; bricoleurs have goals, but set out to realize them in the spirit of a collaborative venture with the machine. For planners, getting a program to work is like "saying one's piece"; for bricoleur it is more like a conversation than a monologue [p. 12]*

It is clear that the definitions of bricoleurs and planners bear a resemblance to Langer's presentational and discursive symbols as well as to Bamberger's Figural and Formal learning modes. Like presentational symbolic system users, and Figural Mode learners, bricoleurs use an intuitive experience-based approach while interacting with computers. Planners, on the other hand, will probably be more inclined to use discursive symbols and formal methods of learning. In the following chapters I will show how these concepts inform my definitions of immersive vs. constructive musical experience as well as high-level vs. low-level musical control. I will also present the manner in which they were embedded in digital musical instruments.

1.4 Music Technology

In this section I will describe experimental and commercial music related technologies, which inform the design and development of the digital musical instruments. I will present a short overview of software as well as hardware innovations, which have been developed during the last few decades for professionals, novices and children.

1.4.1 Interactive Musical Software

The first sounds of computer music were heard in 1957 in Bell Labs in the framework of telephony research [Chadabe 1997 pp 108-110]. Since then, musical software like Music, [Mathews 1969], Csound [Boulanger 1999] and Max [Chadabe 1997, pp. 207-211] have provided professional and novice musicians with new possibilities for interactive sound production, composition and performance. In 1983 composer Luciano Berio suggested that "During the last years it seems that the technological developments have gotten the upper hand and the composer is silenced in front of the means which were created especially for him" [Berio 1983]. Berio's remark addressed the fast pace of technological innovations, which did not allow musicians to deeply and expressively explore a new technology before a newer one was invented. However, in the same year the MIDI protocol [Lehrman 1994] was introduced and completely changed the way in which novice and professional musicians were able to interact with digital music. The Midi protocol's ubiquity and ease-of-use has led to an increasing number of commercial and experimental interactive musical systems, which allowed musicians in different levels to deeply explore the new medium in new comprehensive manners.

One of the firsts to conceptually organize interactive musical systems under one comprehensive scheme was Robert Rowe [1993]. Rowe identified score-driven and performance-driven systems, transformative, generative and sequenced systems as well as player-oriented and instrument-oriented design paradigms. Todd Winkler [1998] elaborated on Rowe's ideas and defined the functionality of interactive music systems in terms of five functions: sensing input, computer listening (performance analysis), interpretation, computer composition and sound generation. These systems, and the theories that accompanied them, were primarily aimed at professional musicians who are computer, as well as, music literate.

Children and novices have also gained from the increasing ubiquity of interactive musical software. Here I will present only a few examples from this very rich domain. Morton Subotnick's "Making Music" [Rothstein 1994] allows children to learn and create music by interacting with a compelling graphical interface. The software includes activities such as moving the mouse over a pitch-time grid and "drawing" musical pieces, or clicking on animated figures, which are placed on a musical staff shaped apparatus, and hearing their corresponding pitches. Although the program does present children with new compelling ways for interaction with computer music, it does not always succeed in providing a deep and expressive continuum between recreating familiar tunes and composing abstract non-guided musical pieces. Toshio Iwai's "SimTunes" [Iwai 1996] takes a more comprehensive animated approach for allowing novices to compose music. Users can create a musical landscape by painting tiles, which represent musical material, on a virtual grid on the screen. They can then manipulate the movement of animated creatures, which generate multiple-layer musical pieces as they step on theses tiles. Different types of creatures represent different musical instruments and different tiles' colors represent different musical notes and timbres. While serving as one of the most innovative and fun interactive composition tools for children, the software does suffer from a number of deficiencies. Since it is based on short musical loops, "SimTunes" does not allow for large-scale interesting musical compositions to evolve. Its limited sound pallet and rigid quantization scheme also impair the musical output. A different, performance-oriented, approach is taken by Harmonix Music's "The Axe." The application allows children to improvise musical solos over familiar musical playbacks by using a joystick or a computer mouse. Users are provided with two degrees of freedom, which are mapped to the height and the length of musical notes. The computer adjusts the users' input to fit the songs' tonality and is also responsible for phrasing the input in a musical manner. While allowing children with no previous musical experience to improvise and enjoy musical performance, the program does not provide an infrastructure for a deep musical interaction. The tonality and phrasing algorithms often limit users to a set of predictable patterns that sounds "right," and do not allow for experimentation with new, out-of-genre, melodies. This tends to impair children's ability to creatively look for their own unique musical path.

1.4.2 Digital Musical Instruments

Current commercial and experimental professional musical instruments offer state-of-the-art solutions in fields like synthesis, sampling, sequencing and recording. Virtual analog synthesizers provide ways to "sculpt" sound, sequencers allow for graphical representation of music, and samplers absorb, manipulate and playback natural sounds from the environment. All of these activities can serve as interesting musical experiences that may be utilized by children in a creative and expressive way. However, the elaborate and precise control that professional musicians seek does not necessarily apply for creative children who are engaged in learning while looking for new ways of expression. As a result, most of the professional commercial instruments lack the responsive and intuitive interface that is so important for children and novices.

An important line of research that *does* allow for connecting ("mapping") intuitive and expressive gestures to meaningful electronic musical output is the augmentation of traditional instruments with electronic sensors, which activate computer music applications. Some examples for such projects are Nicolas Collins's trombone-propelled [Collins 1991], Peter Beyls IR-Violin [Chadabe 1997 p. 223] and Tod Machover's Hyperinstrumetns [Machover 1992], which allowed virtuosi performers like Yo-Yo Ma to interact with the acoustic and the electronic sounds that were produced in correlation with his gestures.

Other interesting efforts to build professional expressive electronic musical interfaces, which are not limited to buttons, keyboards and computer menus, have been made by scholars in STEIM, which also created as set of compositions for instruments like "The Hands," "The web," and "Sweatsticks" [Sawade 1997]. Such instruments map performers' gestures to the generation of algorithmic music or the conduction of prerecorded sequences. Some examples for "conducting-oriented" digital instruments are Max Mathews's Radio button [Chadabe 1997 pp. 231-233] Donald Buchla's Lighting [Chadabe 1997 pp. 227-228] and Teresa Marrin's Digital Button, which used eleven degrees of movement freedom to mix and manipulate music by Tod Machover [Marrin 1996].

Since most of these instruments require a long learning process and high performance skills, they are typically not the most obvious choice for children and novices, who are interested in exploring the interactive music medium. One industry that *has* attempted to use technology in an effort to provide children with intuitive and compelling musical activities is the toy industry. However, its efforts (from "Simon" in the 70s to more interesting efforts from companies like Tomy today) have usually produced poor quality plastic toys that use the musical medium to provide simple challenges and competitions with no apparent musical value.

My personal interest in interactive musical instruments for children evolved from Tod Machover's "Brain Opera" [Machover 1996], which premiered in 1996 and concentrated on providing the general public with expressive and intuitive musical experiences. In the framework of this project, musical instruments like the "Sensor Chair," "Harmonic Driving" and "Rhythm Tree" were developed. These instruments utilized new sensing techniques (such as electric field sensing [Paradiso 1997]) and new musical algorithms that allowed novices to create music with little or no previous musical knowledge and experience. The instruments proved to be especially compelling for children, who returned to the opera set again and again to experiment with them.

The work on the Brain Opera has led Tod Machover's group at the Media Lab to focus on developing expressive musical instruments that can introduce music to children in new exciting ways. As a part of this effort, I was especially interested in the formulation of musical concepts, theories and approaches that would be embeddable in such physical electronic musical instruments. I believe that by developing technological solutions for the theories that I present in this thesis, it will be possible to enhance children's musical experiences and provide them with meaningful expressive and creative activities that could not have been achieved otherwise.

2 PERSONAL MOTIVATION

Before I describe the musical concepts that I formulated based on the theoretical background, as well as my efforts to embody them in musical instruments, I would like to present two stories about the personal motivations for my research. In these stories I present music-related personal experiences in the light of the theories discussed above. In the first story – "My Childhood Object" – I use Piaget's and Papert's ideas in an effort to explain how my interaction with a broken musical toy led me to music composition. In the second story – "Lullaby" – I use Manfred Clynes's "Sentics" and Marvin Minsky's "Society of Mind" notions in an effort to explain some musical behaviors of my son Yonatan at the age of one. Both stories employ Winnicot's "Transitional Objects" and "Transitional Phenomena" notions and can shed light on my personal interest in developing expressive musical instruments for children.

2.1 My Childhood Object

It was a plastic white box with four colored buttons popping up out of its upper surface. Upon pressing each button, a short melody was played from a low quality speaker in its bottom. It was a great toy, best played by hitting the buttons enthusiastically, stopping the melodies after the first several notes, jumping to another melody, and so on. In my initial experience with the toy, rarely a melody had the chance to be played from start to end. The fun, I later rationalized, was in discovering the connection between physically hitting the tactile buttons and changing the sonic environment. But gradually, the music penetrated and I got familiar with the tunes, attributing abstract qualities to some of them. I think I still remember the happy one and the stupid one.

And then the toy broke down.

The first time I pushed a button and nothing happened was frustrating enough to make me remember it today. When no one else managed to fix it I guess I even cried. I never even tried to fix it. I was not interested in the way it worked and whether there were any gears (or anything else for that matter) that I could play with inside the "white box." I wanted to play with the buttons and hear the music. I was interested in the high-level function of the toy. As I'll show later, it came to be the low-level experience of the high-level functionality, which made me write my own first original music. Anyway, my hurt feelings made me dump the toy, which was not to be touched by anyone for a while.

But something drew me back and I tried approaching it again, this time in a somewhat different way. I was pressing the buttons, but since nothing was played, I tried singing the tunes in my heart. Slowly and carefully I tried to reconstruct the melodies, step by step. After each note, I thought really hard about where should I go then – up or down, in a small step or a wide one. I think that after each note that was sang I felt I was *in* the melody, trying to find my way out, not unlike Symour Papert's cognitive and affective assimilation experience with the gears [Papert 1980]. It was a fun "close-to-the-object" approach but the task was not easy. It had been some time since I last heard the tunes and my musical memory was not developed. It probably was then when I first wrote original music, jumping up and down with a melody, trying to keep in mind the parts I liked, getting far away from the original tunes. It could of course have been done without the toy but in a mysterious way, hitting the buttons was much more compelling as a trigger than just walking in the street, singing. Maybe it was the naughty excitement of stopping a melody in the middle by physically pushing another button, trying to start a new melody from scratch.

I recalled this experience some twenty years later while taking composition classes at the university. I was playing a piece that I wrote to a relative who didn't seem to care so much for the piece but rather was amazed by the composition process. He understood that harmony, orchestration and style can be learned but he could not understand how I "invented" the melody. He tried to compare that to language arguing something like: "When I think about a sentence I can build some meaningful coherent structure of words and just say it. When I try to hum a self-made melody, I usually don't know where to go after the first note and when I do know, it turns out to be a popular tune that I already know."

I told my relative about the broken toy experience I had and urged him to try and think that he *was* the last note he sang, trying to figure out where he wanted to go. It was an impossible, frustrating and embarrassing task for him and he quit after the first effort. I cannot tell if that was the lack of an object experience in his childhood, the lack of emotional relation to a musical instrument or something else. He blamed it on his "lack of musical talent," which I could not accept. In this thesis I hope to show that although different innate tendency levels toward music do exist, it is possible to enhance any level towards expressive and gratifying musical experiences that are not substantially impaired by issues like lack of "musical talent."

My physical experience with the broken toy led me to formalize one of the most abstract experiences available to a human being – music. The tactile experience that I had with the toy, the emotions I felt towards it and my hurt feelings when it didn't provide the music that I liked catalyzed this formalization. Years later when I was writing music for a living and understood much more about harmony, counterpoint and structure, I didn't abandon the method of trying to feel the note, trying to figure where it "wants" to go. As a matter of fact some of my best counterpoint teachers encouraged me to do just that, testing if the melody obeyed the rules only after feeling the rules.

The human voice was probably the first "instrument" to be utilized during the "musical evolution" of humankind. Physical instruments came later. But physical instruments and internal "musicality" can and do encourage one another reciprocally. My broken musical toy encouraged me to transfer between the physical instrumental world and my inner uninitiated musical skills. Winnicot [1971] addresses the duality between the inner and outer world and explores the existence of a third transitional stage between them:

> *Of every individual who has reached to the stage of being a unit with a limiting membrane and an outside and an inside, it can be said that there is an* ***inner reality*** *to that individual, an inner world that can be rich or poor and can be at peace or in a state of war. This helps, but is it enough? My claim is that if there is a need for this double statement, there is also need for a triple one: the third part of the life of a human being, a part that we cannot ignore, is an intermediate area of* ***experiencing*** [emphases are in the original text], *to which inner reality and external life both contribute [p. 2]*

Winnicot emphasizes the importance of transitional objects as tools for differentiating between the subjective and the objective. My broken toy presented similar transitional characteristics. The emotional connections that I had developed towards the toy enhanced its transitional nature and led it to "negotiate" between my inner musical ideas and the physical world of instruments and buttons. By experiencing the "intermediate areas of experiencing," I developed emotional tendencies towards the toy, which enhanced my musical exploration process. Winnicot highlights the importance of the transitional phenomena to artistic exploration and argues: "I am therefore studying the substance of *illusion* [emphasis is in the original text], that which is allowed to the infant, and which in adult life is inherent in art and religion..." (p.3). Such "illusory" intermediate experiences also characterized my tune invention and are especially important to the design of artistic musical activities for digital instruments. Influenced by such transitional phenomena, my design will focus on experience-based expressive musical aspects and its transition towards analytical internalization, in an effort to encourage children to explore transitional processes among different musical axes.

One last note: Recently I brought my son a musical toy that I designed. The toy had buttons that activated music in different ways and was connected to a computer for visual and audible feedback. Even though the toy was aimed at a different age group then my son's, he was quite happy to hit the buttons and hear the music (with no apparent understanding of the game's rules). He is a strong little baby and after hitting and banging the toy for a while, unbelievably, a wire got disconnected and the toy stopped responding.

Shall I fix it?

2.2 Lullaby

Since he was a day old, my son Yonatan had difficulties putting himself to sleep. Very soon I discovered that falling asleep was much easier for him when I was singing certain songs in a certain way. The most effective tune (Figure 1) turned out to be the "official good night song" and falling asleep became much easier. The song was most effective when it was sung in a very low register (the notation below is transposed for convenience) and by enhancing bass frequencies in my voice. The preferred tempo was around 60 bmp (pretty slow) and the preferred level was quite low.

Figure 1 - Sleeping Tune

It is hard to say why this specific song had the calming effect that helped Yonatan to fall asleep. Since this phenomenon started just after he was born, I could only try and relate it to pre-birth experiences that he might have had. Maybe the repeated two-note phrase in the first two bars was associated with his mother's heartbeat. Or perhaps it was the low bass frequencies that resembled the ambient effect in the womb. It is even possible that Yonatan was born with a musical taste (we were playing music for him before he was born).

Whatever the case may be, this musical theme proved to have a specific emotional effect on Yonatan. No matter how tense and energetic he was before he was put to bed, hearing this song made him feel more calm and ready to fall asleep. It may be that an early music agent recognized a specific "sentic" [Clynes 1989] that changed Yonatan's mood from tensed to relaxed. At that time I couldn't yet tell where in the song this relaxing sentic was hidden and what were its specific musical qualities.

In the framework of helping Yonatan to fall asleep by himself, we decided to spend only ten minutes with him after he was put to bed. During this time we sang songs to him but when the time came we just left the room. Very often Yonatan discovered our absence and started to cry with anger and frustration. One night, after I left the room and Yonatan began to show signs of tension and anger, I suddenly heard him singing a repeated pattern of a falling 3rd (Figure 2). It was sung in a very high pitch (Yonatan could not yet produce low frequencies) and gradually became slower and weaker until Yonatan was fully asleep. Since then, it became a very useful technique for Yonatan to put himself to sleep and after some time I did not even need to trigger this process by singing any song.

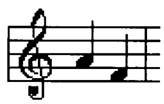

Figure 2 - Falling 3rd Motive

Though transposed and shifted the falling 3rd phrase bears an obvious resemblance to the repeated motive in the first two bars of the "sleeping tune". Now I could speculate as to what was the specific "sentic" and its musical qualities, which were significant for the relaxation effect. The sentic was not necessarily related to the register or specific pitches, rather to the falling interval pattern. The fact that the slower and weaker these repeated intervals got, the sleepier Yonatan became, was probably relevant too.

More interesting was the social role that this "sentic cue" played. Marvin Minsky [1985] suggests that sentic signals can be quite useful in helping infants to learn more about themselves. Minsky's theory would probably suggest that earlier, I used some innate sentic cues (which Yonatan was able to recognize) in order to teach him how to control his emotional state. At first, my external reinforcement was a significant part of Yonatan's learning but eventually he was able to learn from within and freed himself from one aspect of his parental dependency. Music turned out to be an expressive tool for Yonatan in replacing and augmenting an outside teacher (me) with a self-constructed, inner mechanism for solving problems. The problem of having difficulty in falling asleep was solved now by Yonatan himself. I helped Yonatan by using symbols in order to introduce him to an affective state. Then, when he realized that distinct signals could arouse specific states, he was able to associate those signals with those states and produce them himself.

Winnicot (1971) uses children's singing before falling asleep as an example for his "Transitional Phenomena":

> *By this definition an infant's babbling and the way in which an older child goes over a repertory of songs and tunes while preparing for sleep come within the intermediate area as transitional phenomena, along with the use made of objects that are not part of the infant's body yet are not fully recognized as belonging to external reality. (p. 2)*

The process that Yonatan underwent, starting from standard production of random notes when he was younger to being able to repeat intervals that were effective (and affective) for him, resembles the transitional process that I experienced while inventing my new short tunes after my musical toy was broken. Both processes negotiate between the outer world, where familiar music and musical objects exist, and the inner musical world of self invented music. Yonatan approached this process in a similar way to the one that is observed by Howard Gardner [Davidson 1981] - from babbling spontaneous songs to producing "characteristic bits" of familiar tunes of his culture. My experience with the broken toy, on the other hand, moved in the opposite direction. I began with familiar tunes and continued towards inventing my own songs. The deep impact that these transitional phenomena carry was emphasized by the emotional effect that they had on both of us. For me, it was overcoming the frustration of not being able to hear the tunes that I liked and writing my first original music. For Yonatan it was the calming effect that helped him to fall asleep. Although I was older than Yonatan at that time, I was able to "reverse" the process and go back into the creative experience of composing my own music. This serves as an important motivation for my trying to design rich "transitional" musical activities for children, which would be able to encourage creative exploration on multiple musical axes.

Another, seemingly unrelated, interaction that Yonatan had with a different song turned out to be quite interesting in relation to the above observations. Yonatan loved to swing on a wooden swing in the playground. When he was swinging, we used to sing to him another Hebrew song about a swing (by H.N Bialick). The song Nad-Ned uses a jumpy/swingy repeated phrase (C A F) so as to imitate the effect of the swing. After a while Yonatan learned to associate this song with swinging and whenever the song was played on a tape, he started to swing his torso up and down.

I also found out that swinging Yonatan in my hands while singing Nad-Ned turned out to be an effective way for him to fall asleep. I tended to explain this behavior by the physical effect that swinging has on infants. Rocking infants is known to be an efficient way of helping them to fall asleep. Some believe that this action imitates the experience of being in the womb when the mother is walking. (Consider the song "Rock-a-bye Baby" accompanied by swinging movement.) But here, I will try to provide an alternative explanation using the sentic theory.

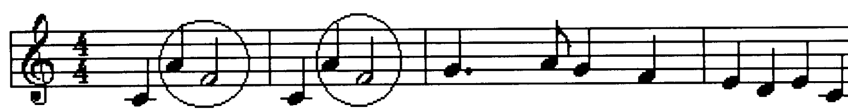

Figure 3 - Nad Ned

As can be seen in Figure 3, each "swingy" phrase in the first two measures ends with a falling 3rd motif, the same motif that Yonatan learned to use as an emotional tool for relaxing, calming down, and getting ready to sleep. I suggest that Yonatan's "sentic" mechanism has been developed enough to be able to perceive more complex music and recognize the falling 3rd motif in a seemingly unrelated song. Often, the way we perceive music has a lot to do with the existing bank of music we already know. Many times different musical tunes illuminate each other, which gives each tune a richer network of "significance." Minsky refers to the reciprocal illumination process: "Dependent circularity need be no paradox here, for in thinking (unlike logic) two things can support each other in midair. To be sure, such autonomy is precarious: once detached from origins, might one not drift strangely awry?" [Minsky 1985]

I believe that Yonatan used this "illumination" process in order to get a richer perspective of the falling 3rd sentic. Yonatan's music perception agency's effectors became multi layered and less limited than it used to be. The agency became more "mature" and could develop a richer set of expressions and interconnections. The falling 3rd motif gained more than one meaning and could relate both to play (swinging) and to sleep. The motive acted as a Paranome that had different meanings in different Frames. When Yonatan gets older, more complex music will hopefully be able to illustrate more ways of compromising and conflicting among different meanings. This may be helpful for understanding the world better, since "things can be meaningful only when they have more than one meaning". [Minsky 1985 p. 207]

3 EXPRESSIVE MUSICAL INSTRUMENTS

3.1 Musical Concepts

In light of the literature reviewed in the theoretical background and my personal experiences, I have formulated three musical concepts, which inform the design of digital musical instruments for children. The musical concepts are the "Level of Musical Control," "Musical Immersion and Construction" and "Interdependent Musical Interactions." In this section I present the musical rationale behind these concepts and elaborate on the different ways in which they interact among themselves. This leads to a detailed description of my efforts to embody these concepts in digital musical instruments so that children would be able to express their musicality in a meaningful and creative manner.

When designing activities for digital musical instruments, it is important to contemplate the different musical modalities of listening, performing and composing. Howard Gardner [1983] addresses this differentiation and claims: "There may well be a hierarchy of difficulty involved in various roles, with performing exacting more demand than listening does, and composing making more profound (or at least different) demands than performing. ...Yet, there is also a core set of abilities crucial to all participation in the music al experience of a culture" [p. 104]. Musicologist Edward T. Cone [1968] goes further in blurring the borders among the modalities and claims, "active listening is after all a kind of vicarious performance, effected...by 'inwardly reproducing the music'".

This border blurring among musical modalities inspired my efforts to formulate new musical concepts that would encourage creative and expressive musical exploration. I have decided to focus on two of these modalities and embed both performance and compositional aspects into the digital instruments. I was interested in extending the traditional notion of instrument performance, which is often based on expressive interpretation of pre-composed written music, towards compositional and improvisational realms, in order to allow children to create their own new and personalized music.

However, unlike conventional improvisational genres (like Jazz for example,) the digital musical instruments cannot yet offer a large body of knowledge or literature from which the performer can quote or paraphrase. As a result new musical esthetics can be developed, which are detached from conventional musical theories of structure or tonality. Since the instruments are designed to address children as young as one year old, they can introduce new intuitive high-level musical controllers, rather than focus on precise note-level traditional musical parameters that are usually appropriate for professionals or for the general public. The new controllers should therefore bear a generic and global nature that is not limited to traditional tonalities or structures, so that they can be implemented and enjoyed by children all over the world before they go through any formal training.

The digital musical instruments' exploratory nature put the compositional aspects of the performance into focus; hence the design of such instruments requires a comprehensive research into the nature of the composing process. The problem, however, is that there are as many viewpoints on this process as there are composers. Here, I will present two different complementary approaches, as they are portrayed by several established 20th century composers. Aaron Copland [1939] addresses the creative "mysterious" elements of composing and attributes them to the source of the original musical ideas. In his view, musical themes initially come to the composer as a "gift form heaven," much like automatic writing. Once an idea has come, the process of development and elaboration follows with surprising naturalness, thanks in part to the many techniques available as well as to accessibility of structural forms, or "schemes" that have evolved over the years. Arnold Schoenberg [1965] continue to elaborate this idea:

> *Whatever happens in a piece of music is nothing but the endless reshaping of a basic shape. Or, in other words, there is nothing in a piece of music but what comes form the theme, springs from it, and can be traced back to it" [P. 186]*

Both Copland's and Schoenberg's views reinforce my relative's bewilderment and amazement in regard to my "invented melodies". They both find the actual development of the composition as an almost trivial analytical process, much like my relative, who accepted the feasibly of developing a melody into a musical piece, but could not understand how I "invented" the melody itself. This analytical viewpoint to the composition process can be easily affiliated with the constructive, formal and discursive notions that are discussed above.

On the other hand, many composers stress the importance of the "close-to-the-object" *experience* as the heart of the composing process. American composer Roger Sessions [1970] articulates a figural, immersive meaning to what he describes as "logical musical thinking":

> *What I have called logical musical thinking is the consequential working out of a sustained musical impulse, pursuing a result constantly implicit in it. It is not in any sense a shrewd calculation of what should happen next. The aural imagination is simply the working of the composer's ear, fully reliable and sure of its direction, as it must be, in the service of a clearly envisaged conception. [p. 110]*

Similarly to my broken toy experience of "feeling" the next note before testing whether it obeys the rules, Sessions does not believe in "shrewd calculation of what should happen next." Rather, he stresses the "musical impulse" and the "envisaged conception" aspects of the composition process. Joining Sessions in underlining the *experiential* nature of composing as opposed to the *analytical* one is Igor Starvinsky, which in another famous remark articulated that "Composing is doing, not thinking" [Craft 1971].

My own compositional experience and the observations that I have conducted (described later), led me to develop a dialectic notion of the composition process, which regards composing as a transitional iterative process between the analytical and the experiential modes. This dialectic approach led to the formulation of the three musical concepts that can be embodied in the digital musical instruments, and allow children to enjoy transitional musical experiences on a set of multiple musical axes. These axes, the "Level of Musical Control," "Musical Immersion and Construction" and "Interdependent Musical Interactions," are described below.

3.1.1 The Level of Musical Control

With the advancements in music recording technology and music distribution methods, a new range of meanings has become associated with what we regard as *playing music*. On one end, *playing music* bears the traditional meaning of interacting with musical instruments for the creation of a musical piece. On the other hand, simple actions like pushing the Play button on a CD player are becoming widely popular ways for *playing music* in modern societies. One explanation for this phenomenon may be the growing ubiquity of friendly digital interfaces which lead modern users to expect immediate responses from the objects around them or at least gentle learning curves for their operation. These limited interactions, however, rarely offer the user high levels of involvement. By limiting the musical experience to a basic interaction with a CD player, one might be deprived of the gratification, fulfillment and enrichment, commonly achieved by deeper musical interactions where meaningful personal contribution is part of the essence of the experience.

One of the premises for the new digital musical instruments' design is that there are intermediate levels of involvement on the axis whose ends are playing the cello and pushing the Play button. By combining discursive low-level controllers with presentational higher-level ones, new musical experiences, which are based on an interaction between these complementary levels of representation, can emerge. These interactions can offer expressive and creative musical experiences without requiring an exhausting learning process, virtuosi performance skills or an extensive body of musical theory knowledge. They can also bridge the gap between different symbolic systems and address bricoleurs as well as planners, figuarlists as well as formalists.

Performance skills and music theory proficiency are usually required in order to master the control of low-level musical building blocks, from single notes to melodies, harmony to articulation. In a traditional music learning process, however, these low-level musical aspects often block the vision of expressiveness, creativity and fun that fortunate professional musicians can experience after a long perfection process. The digital musical instruments' design suggests the use of additional, higher-level, musical controllers as intuitive and expressive intermediate involvement tools. These controllers can be helpful for a more immediate introduction of young potential musicians to the fun aspects of playing music, while still allowing for a rich and meaningful musical interaction. An example for such high-level musical control would be the manipulation of musical "stability" [Dibben 1999]. Digital musical instruments can allow children to interact with such a high-level concept by providing an algorithm that controls interval range, rhythmical consistency, fluctuations in timbre, etc. Another, more generic, intra-cultural example would be the manipulation of melody contour. Psycho-acoustic studies show that two melodies in different scales which share the same articulation, tempo and contour (but not the same pitches) can be perceived as very similar to each other [Schmuckler 1999]. Some experiments show that subjects found such pairs of melodies even more similar to each other than the very same melody played twice with different articulation or tempo. This phenomenon suggests that melody contour can serve as an intuitive high-level control, where users are not generating specific notes, but continuously controlling the abstract "height" of the melody line, based on a pre-programmed scale.

It is important to remember, however, that a deep musical experience should also provide low-level delicate control and accurate manipulation of lower-level musical building blocks. Without these features, the high-level musical experience might lead to vagueness and confusion, which can impede further exploration. A comprehensive control of fundamental musical components (such as accurate pitch, velocity and timing) can motivate players to meticulously construct higher-level musical structures. Being provided with only vague high-level control might discourage such players who prefer delicate, precise and controllable manipulation.

My challenge as a designer of such digital musical instruments for children will be to balance between these two opposite approaches by providing a rich and expressive musical experience that can also allow for low-level manipulation. The instruments that I design should allow for players to smoothly transit between these two ends, taking into consideration that extreme high-level control might not allow for precise exploration, while extreme low-level control might impair expressive and fun aspects.

3.1.2 Musical Construction and Immersion

The concepts of high and low-level musical building blocks provide the grounds for the formalization of another related dialectic, the one between "Immersive" and "Constructive" musical experiences. According to my definition, in an immersive musical experience the players are placed in a complete existing musical environment that provides a holistic infrastructure for them to make sense of and explore. My definition associates immersive musical experiences with an unconscious 'Flow' oriented experience [Csikszentmihalyi 1996], rarely mediated by an analytical musical process. It can also be associated with Langer's presentational symbolic system and Bamberger's figural learning mode. Higher-level controllers serve an important part in designing such immersive experiences, but at times, as I will later show, such environments can also be built out of low-level musical controllers. In constructive musical environments on the other hand, players are encouraged to use small-scale cognitive and physical components (which can be achieved by low-level or high-level controllers) to gradually create their musical experience. The constructive approach is more linguistic-discursive in nature, as the musical components can be perceived as "syntax-based" narrative building blocks. This approach is also formal knowledge-oriented and can be easily approached by planners.

Inspired by the notion that the immersive whole is bigger than its components, some may consider the immersive experience as the sublime musical embodiment. A composer, performer or listener, who cannot elevate themselves towards an immersive, holistic view of the composition, will miss an important aspect of the musical experience. On the other hand, it is clear that an analytical manipulation of constructive building blocks is an important aspect of the creation or the perception of a musical piece. Such constructive approach can be helpful for those who might be frustrated by the abstract nature of the immersive experience. Extreme construction however, bears the risk of losing the 'holistic' nature that is sometimes affiliated with great music. Langer refers to the intuitive, emotional nature of the holistic presentational symbolic system in a way that reflects the immersive nature:

> *It [presentational symbolism] brings within the compass of reason much that has been traditionally relegated to "emotion", or to that crepuscular depth of the mind where "intuitions" are supposed to be born, without any midwifery of symbols, without due process of thought, to fill the gaps in the edifice of discursive, or "rational," judgment....Is it not possible that the sort of "intuitive" knowledge which Bergson extols above all rational knowledge because it is supposedly not mediated by any formulating (and hence deforming) symbol is itself perfectly rational, but not to be conceived through language – a product of the presentational symbolism which the mind reads in a flash, and perseveres in a disposition or an attitude? [p. 97, 98]*

Langer does not want to perceive the presentational symbolic system as a mystical, metaphysical, incommunicable system, despite its amorphous notions like "emotions" and "intuitions." She believes that there are rational ways to describe this system. Like her, I also believe that providing a rational communicable scheme of interaction with immersive systems can be essential for the creation of a meaningful expressive musical experience.

It is important to note that my definition suggests that the immersive and constructive approaches rarely appear in a purified, isolated state. Rather, an *iterative* process of constant transformation between the two complementary perceptual modes often characterizes a deep expressive musical experience. This transitional phenomenon plays a particularly important role in the composition process, where composers use construction methods in an effort to produce a holistic, immersive whole. Often, these methods involve the assembly of discursive musical building blocks based on syntactical rules (melodic, harmonic, rhythmic, structural, etc.). When appropriately constructed, this process bears the promise of composing a whole that is bigger than its parts, where analytical understanding of the building blocks vocabulary can no longer portray the essence of the experience. Similarly to the Paranome agent negotiation role, the transition between these two modes serves an immanent role in the internalization of music's multiple facets.

One of the challenges in designing systems that offer both immersive and constructive experience is to provide a rich and varied infrastructure for different children with different preferences on these axes. A more difficult challenge will be to provide children in the top-down immersive environment with tools for "explorative deconstruction" towards the musical components that is in the environment's core. This can allow "tinkerers" to make better sense of their musical experience. It is equally challenging to encourage children who start at the bottom-up constructive approach to be able to elevate themselves towards the immersive, holistic experience, which may provide them with a coherent musical view for their actions. My efforts to provide such "encouragements" in both directions are described below.

3.1.3 Interdependent Musical Interaction

The third musical axis that I introduce is driven by the motivation to enhance traditional musical interaction with digital technology. Unlike most traditional musical instruments that form direct one-to-one connections between play gestures and musical output, digital instruments can allow for mapping any gestures to any musical outcome. Such connections can open a wide range of possibilities for complex and exciting interaction schemes between players and musical instruments.

I have identified two musical interaction domains, which I was interested in enhancing digitally: the interaction between the musician and the instrument, and the interpersonal interaction among a group of musicians. The first, "individual interdependency" concept is driven by the fact that players of most traditional instruments expect full control over precise musical parameters for every action they perform (from generating notes to articulation and expression marks). This autonomous control can be digitally enhanced by mapping one gesture to several, sometimes partly contradicting, musical parameters as well as by mapping different gestures to the same musical parameter. Individual interdependent musical connections allow gestures, which are being simultaneously controlled by other gestures or musical parameters, to control other musical parameters, or gestures. This definition probably requires an example: Imagine an instrument in which the right hand's continuous gestures control the size of a melodic interval while the left hand's discrete gestures controls the interval's directionality - one button for *up* and another button for *down*. The data from the buttons can also be mapped to manipulate the scale from which the right hand's intervals are chosen while the interval data from the right hand also manipulates the functionality of the left hand buttons. In spite of its dogmatic nature, this basic example presents the wide range of musical possibilities that can change the way in which children interact with musical instruments. In the following chapters I hope to present some of the solutions for intuitive interdependent connections, which I have embedded in digital musical instruments.

The second enhanced interaction domain takes advantage of the new possibilities for configurable digital mappings, which can generate interdependent connections among a group of players or multiple instruments. The "multi-player interdependency" utilizes wired and wireless communication systems in an effort to provide children with new ways of manipulating each other's music in real-time. These kinds of digital enhancements can encourage the exploration of new creative collaborations. For example, imagine a player who in addition to controlling his own instrument, also continuously manipulates another player instrument's timbre. This manipulation will probably lead the second player to modify her play gestures in accordance to the new timbre that she received from her peer.

Her new gestures can also be transmitted back to the first player and influence his music in a reciprocal loop.

While allowing for children to explore networking possibilities in a creative way, a special emphasis should be put on the group's overall output. The challenge here is to allow for the small-scale personal interdependent interactions to function as an integrated part of a coherent large-scale musical output. This challenge can be addressed by a personal mentoring process where children are familiarized with the new musical concepts of collaboration and interaction. It can also be addressed by the aid of musical algorithms that will be developed and implemented in the instruments in order to help children construct a coherent multi-player interaction. While encouraging the players to collaborate musically, the system should not rearrange the players' output in a way that will deprive them of the ability to experiment with individual out-of-the-group experiments.

It is important to note that high levels of interdependency among a large group of musical parameters (or players) can lead to uncertainty regarding the control of each gesture (or player) over its specific role. On the other hand, low levels of interdependency can facilitate a narrow range of interactions, which can lead to a loss of interest on the part of the players. An important research challenge in regard to this dialectic tension is to find interesting connections among appropriate musical parameters that would provide enhanced, yet controllable, collaborations. This will hopefully lead to the definition of new creative balances on an axis whose ends are full autonomy on one side and complex interdependency on the other.

3.2 Early Prototypes

In this section I describe how the concepts of "Level of Control," "Immersion vs. Construction" and "Interdependent Interactions" were implemented in several of the digital musical instruments that I have developed during the last year. These concepts were implemented to different degrees in each instrument. However, in order to provide a clear survey of my preliminary work, I will describe them separately as they were implemented in a number of selected instruments. This short survey will lead to a full description of an *Integrated System* that was designed in an effort to encompass these concepts into one complete environment.

3.2.1 Level of Musical Control

The use of low-level musical control will be described in the framework of the *Sound Sculpture* application, developed for the *Squeezable Cluster* with technical support by Seum-Lim Gan [1998]. High-level musical control will be described in the framework of the *Melody Contour* application, developed for the *SqueezMan* with coding support by Kevin Larke.

3.2.1.1 Low-level Musical Control - Sound Sculpture in the ***Squeezable Cluster***

One of the first instruments to embed different levels of musical control is the *Squeezable Cluster*. The motivation for its development came from examining current commercial and experimental electronic musical instruments, whose interface usually includes accurate and hardened controllers like keys, switches, sliders and computer menus. Such interfaces do not provide responsive and intuitive control and usually interfere with musical expressiveness instead of enhancing it. First efforts to address this challenge have been done in the framework of the Brain Opera and focused on non-tangible sensing of musicians' movements [Paradiso 1997]. These solutions, while providing new expressive means to create and control music, lacked the warmth of a tangible responsive controller. Hence, it was decided to create a soft and organic-feeling instrument that will allow for the continuity of human gestures to generate and control computer-based music.

The *Squeezable Cluster* (figure 4) is made of a cluster, about 12 cm in diameter, of equally sized soft foam balls, each about 6 cm in diameter. Seven pressure sensors (FSRs) are glued at different angles among the balls, and a sensing cube covered with five FSRs (figure 5) is embedded in the cluster's core. The FSRs generate voltage between 0 to 5 volts based on the pressure that is exerted on the balls around them. The twelve channels of analog signal are sent to an I-cube digitizer [I-cube 1999], which converts the signal into Midi [Lehrman 1983] and sends it to a Macintosh computer. Here, a musical application, written in Max [Opcode 1999], interprets the pressure signals and maps them to control musical parameters.

Max is a graphical programming language that is especially designed to receive, interpret and map control data to Midi devices. The control data can be received from commercial Midi controllers, computer devices or any other object that sends serial data. Max programs are written by linking graphical objects that control Midi, logical operations, data handling, timing, arithmetic operations, system devices and more. High-level objects can be created and used in larger programs by encapsulating self-contained Max programs into new graphical objects. New low-level objects can also be written in C language for specific needs that are not covered by the built-in objects.

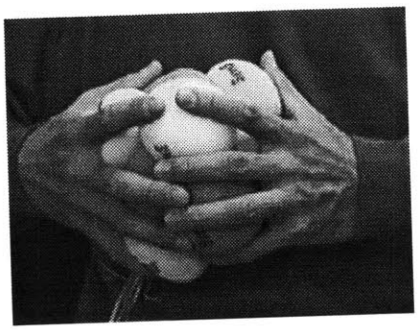

Figure 4 - The *Squeezable Cluster*

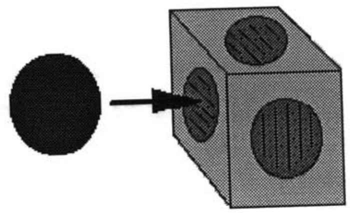

Figure 5 - The Sensor Cube

The *Sound Sculpture* application constructs a complex sound by manipulating twelve low-level interdependent timbre fundamentals. The program receives the twelve channels of digitized continuous pressure data from the sensors and maps them to control the level of timbre manipulators. The sound is generated by two oscillators (a carrier and a modulator) on a commercial Clavia's Nord-Lead virtual analog synthesizer [Clavia 1999]. The user can manipulate the sound ("sculpt its shape") by continuously controlling the level of the following parameters:

- Filter Frequency – controls the timbre's fundamental overtones level
- Filter Resonance – sets the peak frequency in the filter spectrum
- Frequency Modulation – controls the modulation index of the FM generator
- LFO Rate (Arpeggiator Rate) – controls a low frequency oscillator speed
- LFO Range (Arpeggiator Range) – controls the low frequency oscillator's amplitude
- Pitch Bend Range – shifts the fundamental frequency
- Semi Tone Range – controls the tuning between the carrier frequency and the modulator frequency
- Mix Level – shifts between the two oscillators' wave forms
- Pulse Width – controls the carrier oscillator's wave form
- Noise – Controls the level and "color" of noise in the system

The *Sound Sculpture* application correlates between physically "sculpting" the cluster and audibly "sculpting" the sound. The instrument is designed to provide friendly and expressive musical control to low-level timbre fundamentals without requiring a deep theoretical understanding of sound production and acoustics. The soft, familiar foam material was chosen as an appropriate medium for capturing intuitive and expressive squeezing gestures. The accurate one-to-one mapping algorithm (each sensor is mapped to the level of one timbre parameter) is designed to allow users to systematically explore and understand their gestures in relation to the musical output.

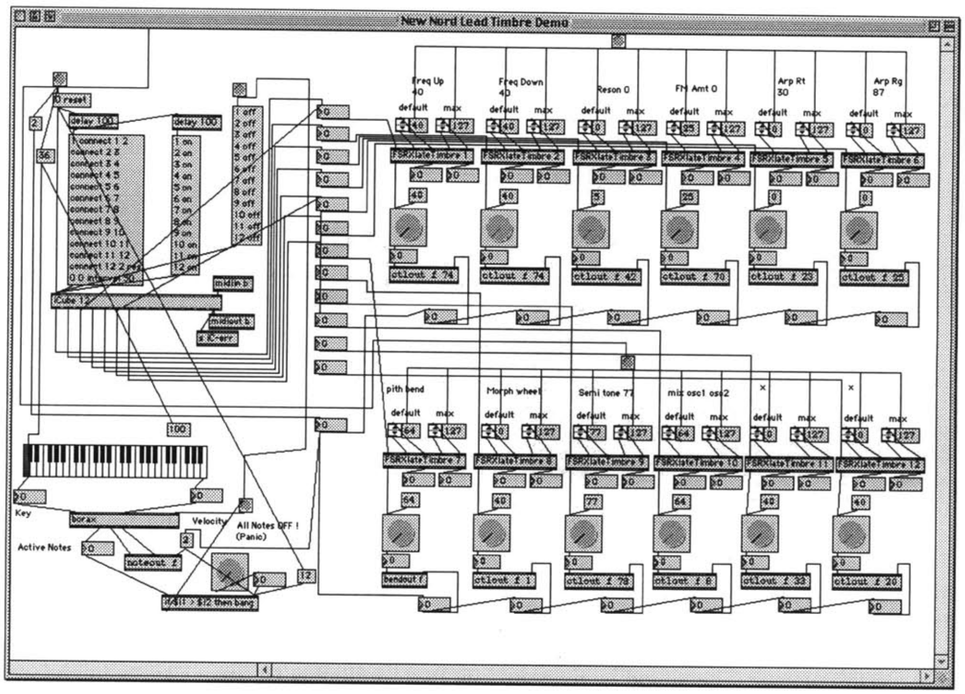

Figure 6 - The Main *Sound Sculpture* Max Patch

The twelve channels (ranging from 0-127) are received by the icube 12 object in the middle right part of the screen. They are sent to the twelve FSRXlate objects, organized as two lines of six objects on the middle left part of the screen. The FSRXlate objects set the active range for each channel and map them, using Midi controller commands, to the respective timbre controllers on the Nord Lead.

The low-level nature of the musical building blocks in this application allows for constructive as well as immersive experiences. Players can begin with a systematic exploration of each sensor's functionality, which can encourage the construction of the complex sound in a bottom-up manner. They can also approach the *Sound Sculpture* application in an immersive manner by expressively molding the cluster and only then moving into exploring the isolated influence of the different building blocks. The immersive nature of the instrument is enhanced due to several interdependent connections between the different parameters. For example, manipulating the Filter Resonance parameter can lead to different "timbral colors", in correlation with the filter cutoff frequency, which is continuously determined by the Filter Frequency parameter. Such interdependent relationships among the low-level building blocks can draw players to expressively experiment with different combinations before moving to an analytical exploration of the exact effect of each sensor.

3.2.1.2 High-level Building Blocks – Melody Contour in the ***SqueezMan***

The *Sound Sculpture* application for the *Squeezable Cluster* was designed to provide children with tactile access to complex issues like acoustics and sound design. However, the application did not allow players to experiment with higher-level, more intuitive, musical experiences like phrasing a melodic line or counter-pointing a number of musical sequences. Moreover, since it was connected to a complex array of musical equipment (including a digitizer, a computer, a midi interface, a sound module, a mixer, an amplifier and speakers,) the *Squeezable Cluster* could not really provide a self-contained, personal sensation. This often impaired children's ability to create affective relationships with the instrument.

The *SqueezMan* was designed to address both these deficiencies. The instrument is a handheld self-contained musical device that maps squeezing gestures to high-level musical parameters like contouring a melodic line. Equipped with a wireless communication system, the instrument also offers a range of interactive musical experiences that take advantage of its ability to manipulate other *SqueezMan's* musical outputs. The *SqueezMan* is made of a semi-transparent plastic container (Figure 7). The electronics and batteries are embedded in the container while the input and output devices are mounted on its top. Two plastic "eyes" are glued on the container to indicate the location of the embedded infrared I/O communication devices, which allow the *SqueezMan* to transmit and receive infrared signals through the semi-transparent plastic.

Figure 7 - The *SqueezMan*

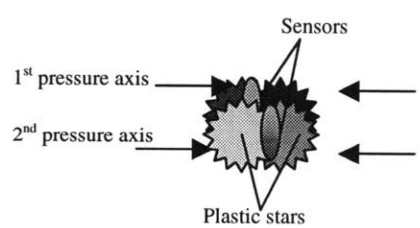

Figure 8 - The *SqueezMan's* Input Device

The *SqueezMan's* input device is made of two force-resistive pressure sensors, which are embedded inside a cluster of four squeezable rubberized star-shaped balls (Figure 8). The sensors generate continuous voltages in response to the pressure levels exerted on each of the two independent pressure axes in the cluster. The ergonomic design allows for two-handed manipulation, using each palm to press against one pair of rubber stars. More experienced users can also operate the device with one hand (a thumb–forefinger axis and a thumb–middle finger axis). This enables performers to hold the device in their other hand and point it toward other user's devices in multi-player mode.

The pressure sensors are wired to two analog-to-digital (A/D) sensor ports on a "Cricket" [Martin 1998] (Figure 9) – a tiny computer that is responsible for the musical engine. The Cricket is based on the Microchip PIC series of microprocessors. It can receive information from two sensors and is equipped with an infrared system that allows for communication with other Crickets. The Cricket is programmed in a dialect of the Logo programming language. Its application programs can be downloaded to the Cricket via its infrared communications system. The *SqueezMan's* Cricket interprets the pressure data from its input device and maps it to musical messages using Cricket Logo general MIDI commands. These are sent via the Cricket's serial bus port to a "MiniMidi Boat" [Smith 1998] (Figure 10) - a tiny General Midi circuit, which supports 16 polyphonic channels, 128 melodic timbres and 64 percussive timbres.

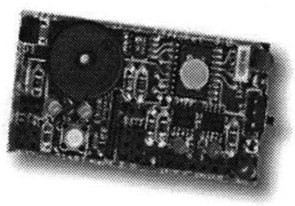

Figure 9 - The Cricket

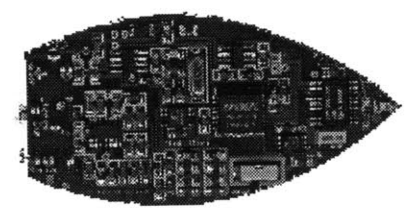

Figure 10 - The MiniMidi Boat

The MiniMidi Boat's audio-out jack is connected to a headphone jack, which is mounted on the device's top. The use of headphones (instead of speakers) imitates the Walkman's solution to the challenge of providing personal local high-quality sound. Like the Walkman, this solution avoids the problem of speakers' quality, weight and power consumption, common to handheld speaker-based devices.

Several different high-level control programs were developed for the *SqueezMan* in order to allow children to intuitively interact with the device. In one application, one pressure channel is mapped to a pitch lookup table. This allows for continuous high-level melody contour control within the active scale. Performers can choose a preset scale (diatonic, chromatic, pentatonic, blues, Indian rags, etc.) and control the height of the melody by continuously squeezing one pressure axis, without having to manipulate specific notes. The second pressure axis is mapped to control the tempo. This axis was initially intended to provide values for a more complex "stability" algorithm that manipulates harmonic modulation, dissonant and consonant intervals, rhythmical consistency, timbre fluctuation, etc. (see musical concepts above). Due to the current Cricket's program memory limitations, this axis was reduced to tempo manipulation only.

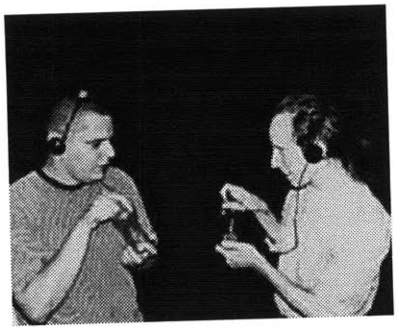

Figure 11 - Multi-User Interaction

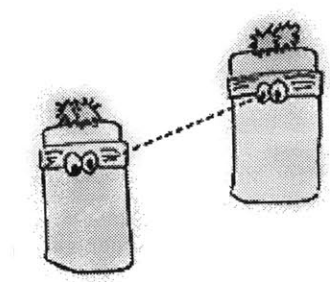

Figure 12 - Infrared Wireless Communication

Several high-level multi-player applications have been developed for the *SqueezMan*. They allow for two performers to hear each other's music through their personal headphones. This collaboration can provide a deeper, more meaningful high-level experience when players learn to coordinate their gestures in order to provide compelling collaborative musical output. In one application a Blues-Scale-Device and an Indian-Rag-Device transmit their musical output to each other. These specific scales (Figures 13 and 14) share 4 notes (C F G and Bb), which can serve as common denominators for scales that are very different in nature.

Figure 13 - Indian Rag

Figure 14 - Blues Scale

Creating musical compositions by continuously controlling several melody contours promises new and exciting ways to experience high-level musical interactions. However, the *SqueezMan*'s limited memory and input resources impaired its ability to construct meaningful and rich musical interactions. The interaction was also impaired due to the headphone architecture, which proved to weaken the musical experience since players could not know exactly what their pears hear at any given moment. Moreover, the instrument could not function as a performing tool since the audience was not able to hear any music at all.

3.2.2 Musical Construction and Immersion

The description of the *Squeezable Cluster* and the *SqueezMan* focuses on the different levels of musical control that they provide. As I have shown, these different levels of control contributed to the creation of both immersive and constructive musical experiences. In the following section I elaborate on the nature of immersive and constructive environments by presenting a set of three instruments. Although these instruments can be played both in an immersive and a constructive manner, I will focus on the immersive nature of the *Musical Candy Bowl* and the *Musical Playpen* (developed in collaboration with Seum Lim Gan [1998]). The *Scaleships* program (developed with coding support by Tresi Arvizo) on the other hand, will serve as an example for a bottom-up constructive environment where players can be elevated towards a more holistic experience.

3.2.2.1 Immersion –The ***Musical Candy Bowl*** *and the* ***Musical Playpen***

Most traditional musical instruments present players with constructive musical experiences by providing an infrastructure for the assembly of pitch, volume and duration values into melodies. Polyphonic traditional instruments also allow players to construct several musical lines into harmonic or polyphonic structures. These bottom-up, constructive musical experiences can be valuable for learning as well as for composing, performing and listening. Constructive musical instruments, however, are rarely designed to elevate novices towards an immersive musical experience that is based on the notion that the musical whole cannot always be perceived as the sum of its components. Constructive instruments can also rarely be enjoyed by infants, toddlers and preschoolers due to the level of logical reasoning and physical skills they require.

The *Musical Candy Bowl* and The *Musical Playpen* address some of the traditional constructive approach deficiencies in providing musical experiences for children. These immersive instruments are based on implementing musical consequence in fun activities that are customarily perceived as *play*. They allows children, who are affectively immersed in these activities, to gradually discover the musical consequences of their motions and navigate their gestures into musical domains. The holistic, immersive experience is designed to serve as a starting point for children's exploration process and not as an ultimate goal, reachable only by an analytical construction process. It allows children as young as one year old to create musical pieces using familiar play gestures and can also encourage older children to deconstruct their musical environment and to gradually internalize basic musical concepts and their contribution to the musical whole.

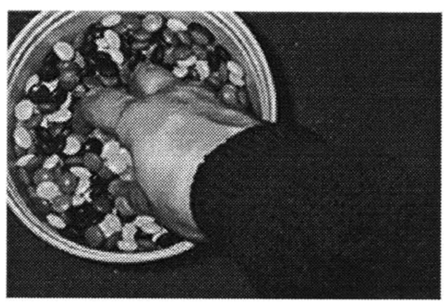

Figure 15 - The *Musical Candy Bowl*

The first prototype to focus on the immersive approach is the *Musical Candy Bowl*, a 3''x3''x5'' plastic container filled with candies. (Candies were chosen due to the positive responses they received from children. They were preferred over wood and plastic beads, foam balls, small air balloons and water balloons.) Children can immerse their hands (fingers, palm and wrist) in the candies and play music by moving their hands in the bowl.

The movements propagate from candy to candy around the bowl and excite 14 pressure sensors (FSRs) that are placed around its circumference. The sensors' data, which represents the location, energy, and trajectory of the hand inside the bowl, is digitized and converted to MIDI. The data is then sent to a Macintosh computer where it is mapped to musical parameter control by Max.

In one application, each sensor manipulates the level of one arpeggio[1] parameter. The parameters are the register, interval width, speed, duration, accentuation and timbre of the notes. (See a complete description of this application in the section about Interdependency.) Due to the vague nature of the system (there is no direct contact between the hand and the sensors), different sensors are simultaneously triggered at different levels so interdependent connections among the musical parameters are formed. The output is therefore an ever changing, fuzzily controlled stream of music, which children can explore by delicate manipulations of their gestures. The high-level, intuitive nature of the arpeggio's building blocks can encourage users to "dive down" and manipulate them separately. However, due to the high-level nature of the building blocks and their complex interdependent connections (see below), players may find it difficult to reconstruct the music by starting at the note level. This use of high-level controllers intensifies the instrument's immersive nature and impairs the possibility for creating an analytical constructive experience.

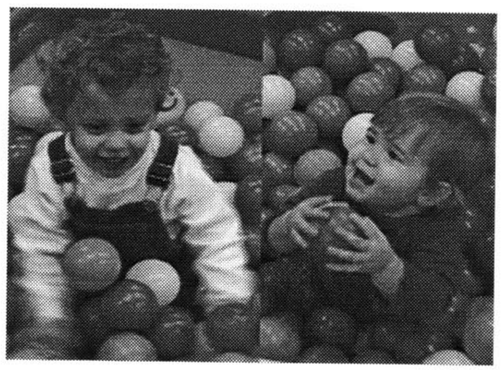

Figure 16 - Two Infants Play the *Musical Playpen*

The *Musical Playpen* is a whole-body enlargement of the *Musical Candy Bowl,* which was developed in an effort to provide better constructive infrastructure while allowing for an embracing physical immersion and full-body (four limbs, torso and head) musical exploration. In order to allow for gradual musical internalization of fun play gestures, it was decided to use a play space that is compelling for children even without musical affiliation - a 5'x5' playpen filled with 400 colorful balls. The playpen's musical output is generated in correlation with the players' position, location and level of energy. Here too, the players' movements propagate from ball to ball and trigger different sensors to different degrees. The players' motion data is received from piezo-electric accelerometers that are

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[1] A term used to describe the pitches of a chord as they are played one after the other, rather than simultaneously.

hidden inside four selected balls around the playpen's corners. The analog data is then digitized and sent to a Macintosh computer running Max.

The *Musical Playpen* application maps two of the playpen's corners to a pitch look-up table that represents an Indian Rag scale. The more accelerated the body movements in these corners are, the higher the Indian rag pitches get. The other two corners control a percussive section where sensor acceleration is mapped to a drum sound look-up table. The drum table contains low drums in the lower range (bass drums, tablas), higher frequency percussive sounds in the middle range (snares, tam-tams) and high frequency sounds in the highest range (high-hats, cymbals, crashes). For both look-up tables, a low-range random generator provides velocity and duration values in order to generate a more dynamic musical output.

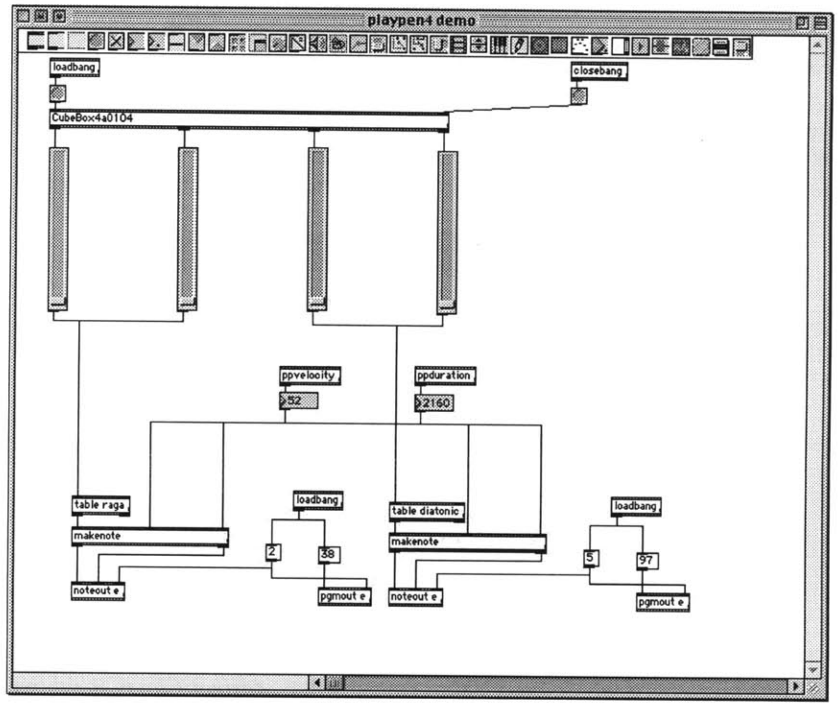

Figure 17 - The *Musical Playpen* Max Patch

Acceleration values from the four corners are received, parsed and analyzed by the CubeBox4al04 object. Based on the sensor data, the object then sends Midi note-one commands to two melodic and percussive lookup tables. The ppvelocity and ppduration objects provide random values for the makenote generator.

Since it is difficult to control specific sensors individually (unless being told, the player does not know in which balls the sensors are hidden), an immersive effect of generating holistic musical output in relation to interdependent movements can be created. However, due to the simplicity of the basic algorithm (low level one-to-one mappings between the level of acceleration and the notes' height), interested children can gradually explore the exact connections between their gestures and the musical output. By learning to control their play gestures in the Indian rag corners, children can internalize musical concept such as scale, pitch and height while expressively experimenting with creating their own "Indian phrases". By accurately manipulating the drum corners, children can experiment with different drum sounds and internalize concepts like frequency and timbre.

The *Musical Playpen*'s high-level contour manipulation contributes to the immersive nature of the instrument, but unlike the *Musical Candy Bowl*, the instrument can allow for a certain degree of constructive exploration due to the simplicity of its core algorithm. However, this simplicity, which is based on only one degree of freedom in each corner, also bears a downside, as it does not allow for composite, more interesting interactions to take place. The instrument is therefore suitable for infants and toddlers, but older children usually found it non-challenging. This downside was enhanced by the non-accurate piezo-electric sensors that were used for sensing players' movements. These sensors did not allow for precise, delicate and tightly controlled manipulations for children with well-defined musical goals. A more complex constructive system, which provides a rule-based accurate control for older children is the *Scaleships* program, which is described below.

3.2.2.2 Construction – ***Scaleships***

Scaleships is a computer program that was developed as a prototype for a future physical toy. The program (which is currently only implemented in software) is influenced by Kwin Kramer's "Tiles" [Kramer 1998], a computerized physical construction kit, in which powerful computation and communication are built into kid-scale blocks. The Tiles allow children to generate sequences of lights in different colors that propagate to other Tiles via infrared communication ports. By interacting with the Tiles children can experiment with dynamic patterns, create "communities of toys" that interact with each other, write programs that move from Tile to Tile, and "create rich arrangements of overlapped atoms and bits." [p. 2]

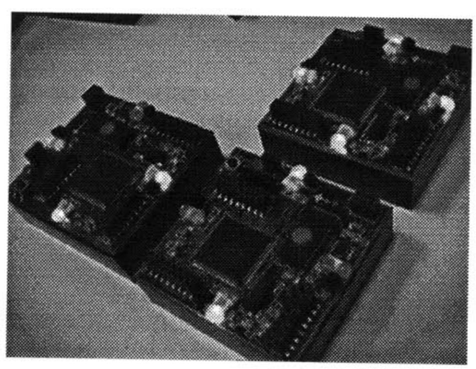

Figure 18 - **Kwin Kramer's Tiles**

The *Scaleships* program simulates a musical application for such a community of physical Tiles. The rationale is to generate rule-based musical sequences that move from Tile to Tile and enhance the visual "emerging community" with a dynamic musical community that is based on simple decentralized rules. The software prototype for this system uses a 4x4 virtual grid on the screen, which allows users to create (or remove) a total of up to 16 objects (ships); each is able to communicate with its four closest neighbors. After creating a ship by clicking on an empty spot on the screen, users can use its default musical characteristics, or configure its new "musical character" by setting up the following parameters:

1. Timbre – choosing a timbre out of 127 General Midi sounds.
2. Register – setting a low and high pitch limit. Range: C0 to B7.
3. Rhythmic values – controlling a high-level algorithm that sets the percentage of eights, triplets, fourths, half notes and whole notes. The user is provided with one slider which ends are "fast notes" to "slow notes."
4. Velocity – setting low and high velocity limits. Range: 0 to 127.

These characteristics are inherent to each ship and can only be changed by using the above dialog box. Other ships cannot manipulate or control these parameters during the real-time interaction.

Each ship also has a number of real-time controllers:

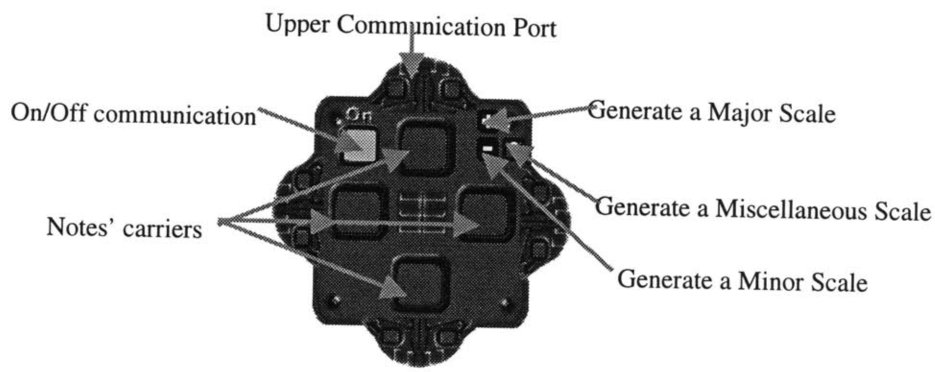

Figure 19 - ***Scaleships'* Functions**

1. On/Off communication button – Turning this button on activates the ship's four "communication ports." This allows for musical lines ("snakes") that are created by the ship (or that are passing through it) to propagate to its neighbors. When the communication button is turned off the ship will not send or receive musical lines. Any existing or future musical activity in the ship will be captured within itself.
2. Generate a Major Scale – Pressing this button cycles through the musical "cycle of fifths". The longer the button is pressed, the more accidentals are added to the scale. The sequence is – C, G, F, D, Bb, A, Eb, E, Ab, B, Db, F#(Gb). On mouse up, the current scale becomes active and generates the musical "snake."

3. Generate a Minor Scale – same as above but with minor scales.
4. Generate a Miscellaneous Scale – same as above but the cycle goes through miscellaneous scales, which start on C. The sequence is: Whole note scale, diminished scale, chromatic scale, blues scale, Indian rag, Arab Makam.

After a scale is set, four of its notes are chosen by an algorithm that gives 70% weight for the root notes (1, 3, and 5,) and 30% weight for the other notes (2, 4, 6 and 7.) Miscellaneous scales' notes are exceptional – they are chosen on a random basis with no weight assigned. The chosen scale is presented in the ship's center while the four notes are assigned to a carrier in each side of the ship, a note per side. The different scales are graphically represented by color dots – red for major scales, blue for minor scales and yellow for miscellaneous scales. The chosen notes start to play immediately and create the melody "snake" which loops around the ship. The ship's musical character is applied to the snake by the pre-determined characteristic settings: timbre, rhythmic and velocity values. The rhythmic values are changing dynamically within the chosen range in order to provide a "live" feel to the ship's music. In any given moment the user can generate another scale, which replaces the current scale by generating four new notes.

When the ship's communication system is turned on, the musical snake can propagate to a neighbor ship. The snake carries the scale, timbre and volume values of its original ship and receives the new ship's rhythmical values and register. If the new ship's communication system stays on, the snake continues to propagate to other neighbor ships bringing with it some musical parameters and receiving some new parameters form each ship it passes through. If there is no receiving neighbor, the snake loops and turns back in its tracks.

The program is designed to allow a "social" musical interaction, which evolves from the tension between the ships' musical character the visitor snake's musical character. The socialization becomes more interesting when several snakes (carrying different scales, timbre and volume settings) are generated in different places around the grid and through various ships. This allows the player to experiment with creating polyphonic and polyrhythmic lines of different scales. In any given moment the user can add new snakes in different scales, terminate existing snakes (by removing their current ship), turn different ships' communication system on and off, or add and remove ships from the screen. The user can also globally control the tempo, volume and directionality of the snakes.

At preliminary levels, programming the different ships and carefully adding complexity to the system allow the user to investigate how complex multi-channel systems can evolve from the construction of small-scale, rule-based building blocks. However, due to the high-level nature of these blocks (scales, percentage of rhythmic values, etc.) and the large number of "snakes" that can flood the system, this low-level construction kit can rapidly evolve into higher, more immersive levels. In a fully developed system, a single mouse click will probably be noticeable only as a delicate vague change in the rich complex sonority. The system encourages a gradual switch from analytical constructivism to expressive immersion, where intuitive and emotional decision-making can be more effective than discursive examination.

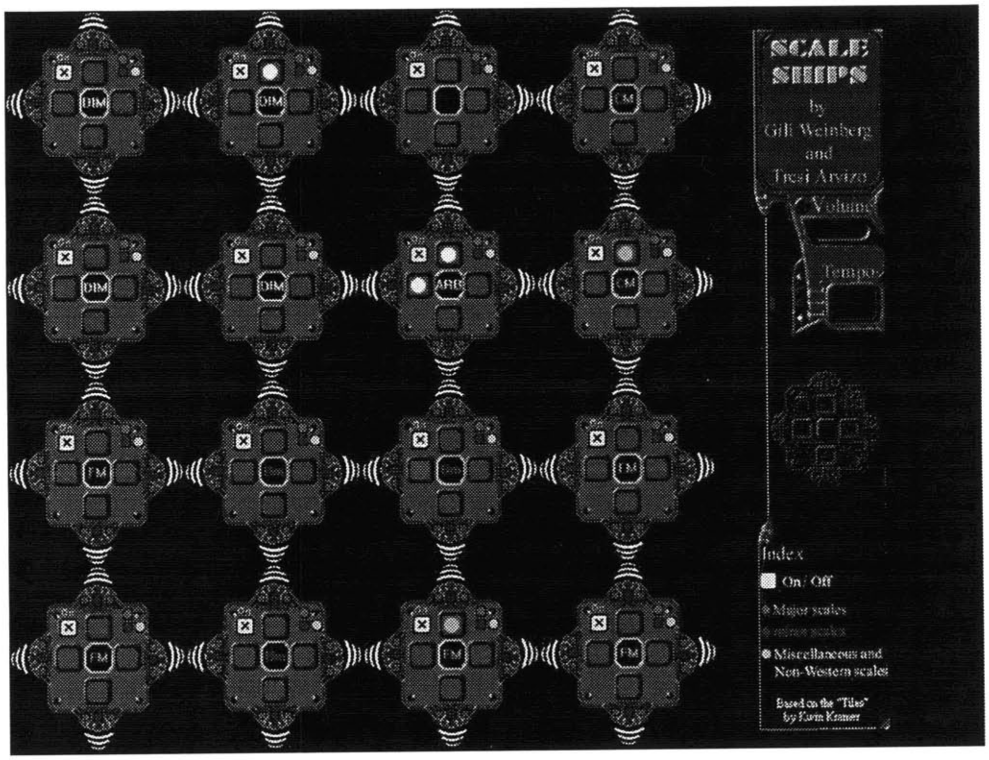

Figure 20 - A Full-Scale (4x4) *Scaleships* Array

The main drawback of the *Scaleships* program is the lack of musical directionality that it provides. Due to the self-evolving nature of the system, it is difficult for users to create a musical piece with a beginning, middle and an end. The program also does not allow for the construction of different sections into a full coherent piece. Like other generative algorithmic musical systems [Koan 1999], *Scaleships* was criticized for providing a "wall-paper-like" ambient musical output.

3.2.3 Interdependent Musical Interaction

One solution for the non-directional nature of generative musical instruments is to provide players with continues control over high-level aspects of the music, so coherent directionality will be in the players' control. It is also possible to implement in such instruments a number of different modes, from which the user will be able to construct a dynamic progression. In this section I will describe the *Arpeggiator*, an interdependent applications that was the developed as a new musical mode for the *Squeezable Cluster*. The *Arpeggiator* application demonstrates how internal interdependent connections for individual use can allow for continuous manipulation of generative musical algorithms.

The section also presents the *Squeezadelic* application for the *Table of Squeezables,* which demonstrates a scheme for interdependent connections among multiple players.

3.2.3.1 Internal Interdependency – The Arpeggiator in the ***Squeezable Cluster***

The *Arpeggiator* application was developed with Seum-Lim Gan [1998] for the *Squeezable Cluster* and was later used in the *Musical Candy Bowl.* Here I will present it as an example of a system that allows a single player to simultaneously control several high-level interdependent musical parameters. The *Squeezable Cluster* was modified for the *Arpeggiator* application so as to send only six channels of continuous control rather than its possible twelve channels (two sensors were mapped together to one input channel). The six channels provide values, ranging from 0 to 127 based on the level of pressure exerted on the instrument at different angles. The data is then sent through an I-cube digitizer to a Max program and parsed to six sub-patches that control the arpeggio engine. The sub-patches are:

- RegisterSelect – controls the octave range in which the arpeggio plays. The higher the input values are the larger the range is (range varies form a minor second to eight octaves).
- IntervalSelect – calls for twelve different interval sequences in relation to the input values. The higher the input values are, the less diatonic and more chromatic the intervals become.
- AccentSelect – reads a sequence of accented note occurrences. The higher the input values are the more accented notes are generated. The objects create an effect of an additional musical line (or melody) since the accented notes are perceived as a continuous line, played in parallel to the non-accented notes.
- HoldSelect – reads a sequence of notes' length value occurrences. The higher the values are the more "long notes" are being played. The input values also control the length of the "long notes" - the higher the input values are the longer the long notes become. The object creates a harmonic effect since some of the long notes are still being played along with the shorter notes that follow them.
- InstrumentSelect – A sequence of twelve program changes is called. The higher the input values are the more bell-like and percussive the timbre gets.
- Tempo – The higher the input values are, the faster the tempo is. (range varies from, 120 bits per minute to 250 bits per minute.)

These sub-patches send their output to the PlayNote object, which generates the arpeggio notes, by sending Midi commands to a commercial sample player, the E-Mu's UltraProteus [e-mu 1999]. The *Arpeggiator* starts playing from middle C up to the high pitch limit, which is continuously determined by the RegisterSelect object. The high limit pitch serves as a turning point where the notes change direction down to the low returning point (also continuously determined by the RegisterSelect object) where they change directionality again and so forth.

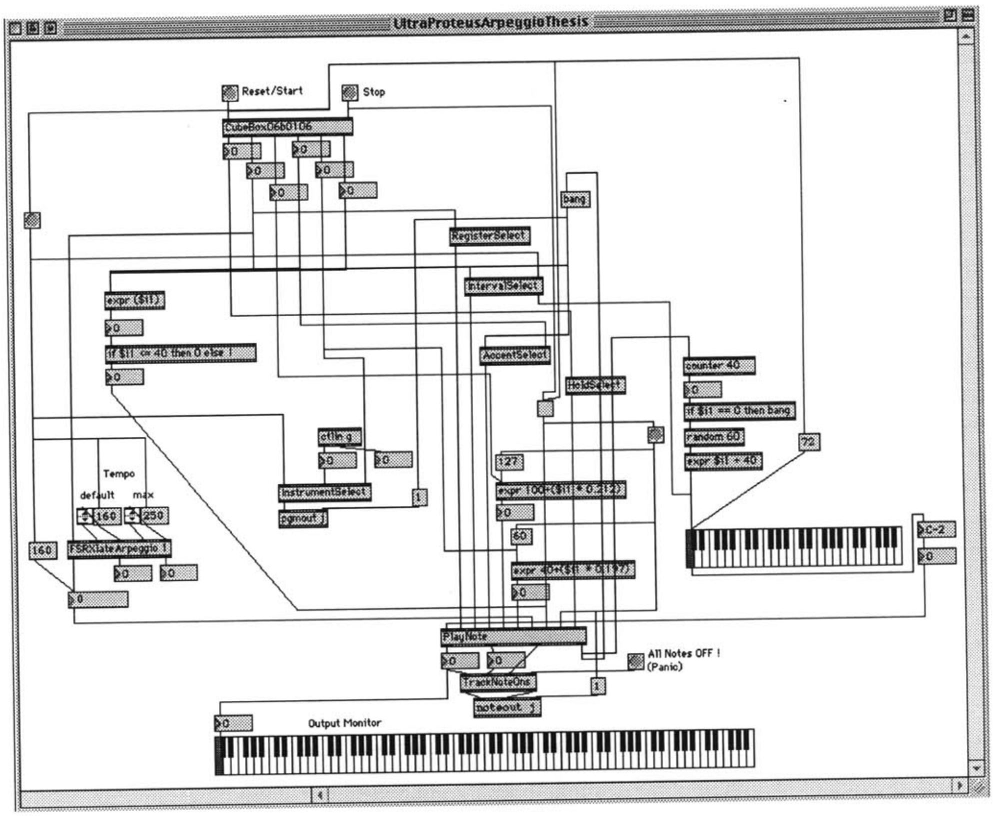

Figure 21 - The *Squeezable Cluster Arpeggiator* Max patch

The CubeBox06b106 object sends six continuous channels to RegisterSelect, IntervalSelect, AccentSelect, HoldSelect, InstrumentSelect and Tempo. Based on the input, these objects sends note-on and note-off instructions to PlayNote.

The internal interdependency effect is caused by the simultaneous manipulation of the six arpeggio parameters. As an example, I will describe the interdependent influence between IntervalSelect and RegisterSelect: When the RegisterSelect is set to 0 (no input from the instrument), the IntervalSelect has no influence at all since no music can be played without an effective register range. When the register values increase (due to stronger squeezing actions at the relevant angle), the very same IntervalSelect values can cause a different set of notes to be played depending on the high and low returning points that are set by the RegisterSelect. A minor 3rd interval when played in the proximity of two semitones to a high limit turning point will cause the new set of notes (in the other direction) to start one semitone below the turning point. (The 3 semitones in the minor 3rd interval "goes" up two semitones and then another semitone down.) This shift changes the tonality of the *Arpeggiator* altogether. The accented melody (generated by AccentSelect) is also influenced by these interdependent connections. AccentSelect generates accented notes based on a sequence of occurrences; it does not "know" what the specific notes are that will be accented. Thus, the melody will continuously change based on the different values that are generated by these three interdependent objects. It is easy to imagine how adding the other three objects to this equation complicates the interdependent influence even further.

Another factor that contributes to the complexity of the interdependent connection is the *Squeezable Cluster* hardware design. Since the instrument is held in both hands, it is relatively difficult to squeeze only one isolated sensor and to manipulate only one isolated arpeggio parameter. It is impossible to have a "non-squeezing" hand since each hand must provide contra force in order to allow for the other hand to squeeze in the desired axis. This contra force unavoidably exerts pressure on at least one additional sensor that manipulates at least one additional parameter. The placement of the sensors among the balls also contributes to the internal interdependency. The different angles at which the sensors are mounted make it difficult for the user not to trigger a cluster of neighboring sensors. Due to these factors, it is almost impossible to fully explore the *Arpeggiator's* parameters and to control them separately.

3.2.3.2 Multi-player Interdependency – Squeezadelic in the ***Table of Squeezables***

Two main challenges evolved from the *Squeezable Cluster's* design. The first was to define new, more controllable, balances on the axis of autonomy vs. interdependency, so players will be able to better isolate and internalize the musical concepts at hand. The second challenge was to broaden the idea of interdependency into group playing situations, so different users will be able influence each other's music and experiment with new ways of musical collaborations. These challenges lead to the devolvement of the *Table of Squeezables,* the first multiple-user instrument that allows for interdependent connections among its players.

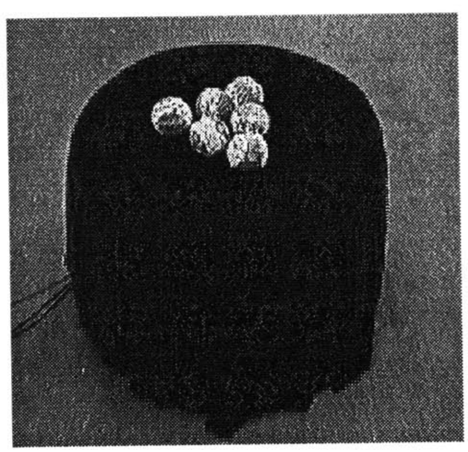

Figure 22 - The *Table of Squeezables*

The instrument (developed with Seum-Lim Gan [1998]) is made of six gel balls, installed on a small round table. Sensors inside the balls and below the table sense the players' gestures. The data is then transmitted to a computer, which interprets and maps it to musical sequences and timbre control for the creation of an original musical piece. The sensing devices in the *Table of Squeezables* are designed to provide a soft, organic and responsive control. The gestures that were chosen for the instrument are squeezing and pulling – familiar, intuitive, continuous actions. Several materials have been tested as providers of such a control. For the final prototype, soft gel balls were chosen. These proved to be robust and responsive, providing compelling force feedback impression, which is derived from the elastic qualities of the gel.

Buried inside each ball is a 0.5x2.0 cm plastic block covered with five pressure sensors (similar to the *Squeezable Cluster*'s Sensor Cube), protected from the gel by an elastic plastic membrane. The continuous pressure values from these sensors are transmitted to an I-cube digitizer and converted to Midi. The pulling actions for each ball are sensed by a variable resistor in a slider form that is installed under the table. An elastic band is connected to each ball, which adds opposing force to the pulling gesture and helps to retract the ball back onto the tabletop. Here too, a digitizer converts the signal to Midi and transmits it to the computer.

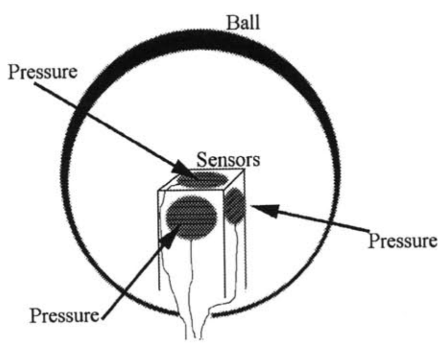

Figure 23 - The Sensor Block

The combined signal indicates the level of squeezing around the ball

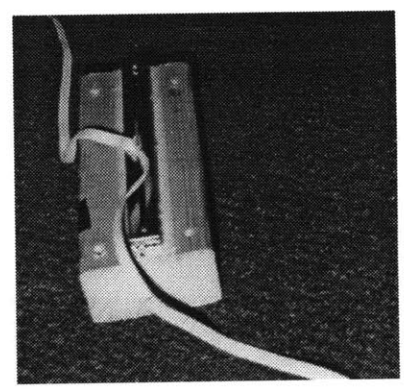

Figure 24 - The Variable Resistor Slider

One slider for each ball is installed under the table.

The digitized data from the players' pulling and squeezing gestures is transmitted to a Macintosh computer running Max. The main *Squeezadelic*'s Max patch forms interdependent connections among the different players. The patch divides the balls into five accompaniment balls and one melody ball. Three of the accompaniment balls serve as "Sound Sculptors" by controlling continuous timbre characteristics of an analog synthesizer. These balls are mapped to manipulate a Nord Lead II [Clavia 1999] virtual analog synthesizer's parameters, such as wave shapes, envelopes, filter, resonance, noise, LFO, modulators and FM. The other two accompaniment balls are mapped to pattern generation and manipulation algorithms, which control the rhythmical complexity level and the timbre of pre-recorded sequences (generated by Steinberg Rebirth application [Steinberg 1999]). These balls contribute a sense of rhythm to the first three balls, which are more abstract and "ambient" in nature.

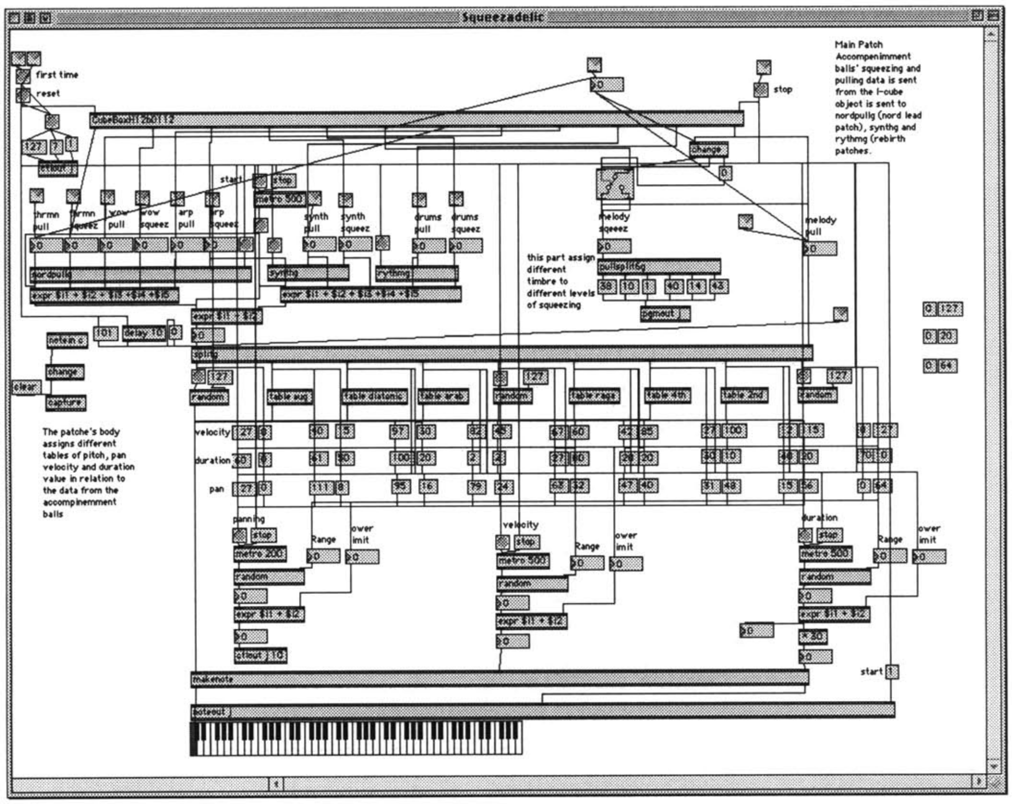

Figure 25 - The Table of Squeezable Max Patch

> *The CubeBoxH12b0112 sends 6 channels (from 3 balls) to the nordpull object which is responsible for the timbre manipulation, 4 channels (from 2 balls) to the synthg and rythmg objects which are responsible for the percussive part, and 2 channels (from the melody ball) to the algorithm in the low part of the screen which receives its values from the other 5 balls.*

As was mentioned before, previous developments of interdependent mappings indicated that a high level of interdependency between different players creates uncertainty about the control of each player. On the other hand, little interdependency can create a narrow-ranged repeatable outcome and eliminate the sense of collaboration and surprise. The *Table of Squeezables*' solution to this tension is to allow for the five accompaniment balls to have full autonomous control over the accompaniment. No input from other balls can influence their output. However, these balls' output has an important influence on the sixth ball – the "Melody". Pulling the "Melody" ball activates an algorithm, which reads lists of pitch, velocity, duration and pan values. These values are determined by the level of activity (pulling and squeezing) in the other balls and allows for the accompaniment balls to "shape" the character of the melody. By squeezing "Melody," the player can directly control its timbre as well as manipulate the accompaniment balls' weights of influence over its own output in an interdependent loop. This solution takes into account that different players in the ensemble serve in different roles, hence they are provided with different levels of interdependency.

As a test case for these mappings, a piece was composed for the instrument. The 6:25 minute piece, named *Squeezadelic*, is based on the tension between the continuous accompaniment balls and the discrete melody ball, which is being shaped by them. The piece starts with a high-level of melody instability and is built gradually towards a more ordered pick where all six balls are playing in a psychedelic feel (from which the piece derives its name). This tension is enhanced by the accompaniment balls' electronic synthesis-based sound as opposed to the more natural, sample-based timbre of the melody ball. While the piece progresses, different scales are being called by the melody ball with relation to different accompaniment balls' activity. Changes in the balls' activity alter the melody from harsh 4th-based intervals through a widely panned Indian rag sequences, to a staccato Arab scale, etc. The long, monotonous rhythmic ending functions as a balance for the less stable body of the piece.

Figure 26 - The *Squeezadelic* Performance

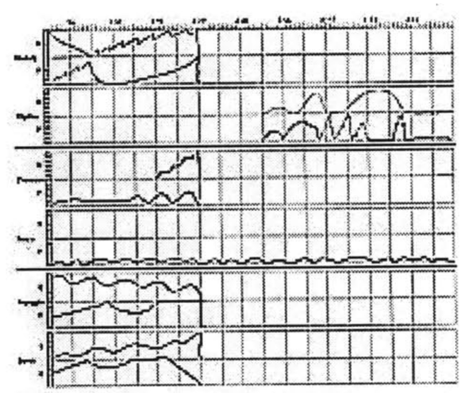

Figure 27 - The *Squeezadelic* Score

Special notation was created for the piece. Two continuous graphs were assigned for each of the six balls. One graph indicates the level of squeezing over time and the other indicates the level of pulling. After learning the score by heart, three players performed the piece, playing two balls each. In certain parts of the score, the players were encouraged to improvise and to give their own interpretation of the written music. By paying close attention (both to each player's personal musical output and to the interdependent control on other balls), the players modified the written piece and created their own versions. The performance was videotaped several times and later edited for public presentation. [Weinberg 1999].

A detailed reflection on the performance of the *Squeezadelic Table* is presented in Chapter 4 "Observation and Reflection". Here I will limit myself to pointing out some of the main deficiencies that were found in the instrument. The heterogeneous nature of the system, although being helpful in preventing confusion in regard to the interdependent scheme, narrowed down the functionalities of the different balls. Players of the accompaniment balls for example, often found controlling these balls too simplistic and closed-ended due to their lack in interdependent input. On the other hand, the melody ball players often found it too complicated to control, due to the large amount of interdependent data that had to be processed in real-time.

The group playing interaction was also impaired at times due to some design choices that were made as to the internal and external control of the musical parameters. For example, preventing the melody ball player from having full control over the melody notes' velocity values damaged his ability to phrase meaningful musical lines. On the hand, the full control that the melody player received over the timbre could have been subjected to enriching interdependent influence without impairing the musical coherency. Another problem that was detected is the lack of individual interdependent connections between specific balls. Since only the signal sum from the accompaniment balls served as a parameter in the melody ball's algorithm, it was very difficult for a specific player to significantly manipulate the melody, without trying to coordinate such a maneuver with the other accompaniment ball players. These deficiencies were addressed in the design of the *Integrated System,* which is described below.

3.3 An Integrated System

The concepts of high and low musical control, immersive and constructive musical environments and interdependent musical connections were formulated and refined during the development of the instruments that I described above. Each instrument focused on selected aspects of the musical experience and as a result encouraged different play patterns. In order to provide rich and expressive experiences for a wide range of children with a wide range of play tendencies, it was decided to develop an *Integrated System* that will allow for different users to transit among the three main conceptual axes:

Low-level Control	⟷	**High-level Control**
Constructive experience	⟷	**Immersive experience**
Autonomy	⟷	**Interdependency**

Such a system can provide a complete musical infrastructure for bricoleurs as well as planners, dramatist as well as patternists, figuralist as well as formalists, individualists as well as group players. It also bears the promise of allowing players in different musical starting points to undergo transitional processes towards other axes' ends, which can help players to reach a deeper appreciation of the musical experience.

3.3.1 Design Rationale

The system is comprised of three modules that can be seen as three separate instruments as well as three different modules of one complex instrument. The modules are:

- *The Squeezable Voice Ball* – a microphone is embedded inside a soft ball which is covered with eight conductive fabric electrodes. Players can sing into the microphone and manipulate effect processors on their voice timbre in real-time by squeezing the fabric electrodes.
- The *Digital Talking Drum* – a conga-shaped soft drum that can be hit and squeezed. Hitting the drum triggers an enveloped sound that is based on the processed timbre from the *Squeezable Voice Ball.* Squeezing the drum manipulates a delay algorithm on this sound.
- *The Mixing Bowl* – an electric field sensor is embedded inside a wooden bowl. Movements inside the bowl are mapped to pitch and velocity contours, which are based on an arpeggiator that receives its parameters from the other two modules.

The rationale behind the module-based-architecture is to allow different users to play the system in different ways: constructivists may see it as three separate instruments, while immersionists will probably play it as a full interconnected whole. The system was designed so that during the performance, players will be able to go back and forth among the different points of view and explore different balances on the various axes. The system is highly interconnected while players are provided with a variety of activities in which they can influence other players' music. The system is designed to allow individualists to be able to have meaningful control over their music while allowing group players to "open a gate" to external influence when desired. The system is also designed so that players will be able to explore different levels of control, immersion and interdependency in real time and define their own preferences.

An important design goal was for system to allow for the three conceptual axes to be as autonomous as possible. It was desired that users would be able to have a wide range of permutations: from creating an immersion experience using low-level interdependent building blocks, to generating a constructive system that uses high-level autonomous building blocks and so forth. The three conceptual axes guided the implementation of the *Integrated System* so that high and low-level control, construction and immersion as well as different levels of interdependency would offer a wide range of activities to a wide range of users. The system incorporates a varied array of control levels that can be accessed in real-time by the different instruments - from the discrete low-level *Digital Talking Drum* to the continuous high-level *Mixing Bowl.* Each instrument's algorithmic flexibility also allows for the exploration of different levels of control within each instrument. For example, at its core, the *Digital Talking Drum* is a low-level controller. Players can control the exact timing, velocity and length values of each hit in a one-to-one connection with their gestures. But the drum also allows shifting to higher control levels by squeezing it between the player's legs. This gesture manipulates the delay time algorithm so that the stronger the drum is squeezed the shorter is the time between each delayed repetition. Based on other delay parameters (such as the feedback loop time, which is controlled by the *Squeezable Voice Ball*) this gesture can provide a higher-level experience since the different drum sounds are no longer only reflecting the discrete player's hits. With a long delay feedback loop, it is difficult to distinguish between the physical hits and the digitally delayed repeated ones. This allows for continuous squeezing gestures to serve a prominent role in controlling higher-level musical aspects such as the "rhythmical complexity" or "percussive density." Players can transmit among different control level and decide if and how much delay time manipulation is applied by squeezing the drum in different manners. The other players (like the *Squeezable Voice Ball* player for example) can also influence the level of control by manipulating other delay parameters with their own gestures.

Another example of multiple control levels that are offered to a player by one instrument is the contour manipulation in the *Mixing Bowl.* Due to the accuracy of the electric field sensor and similarly to other continuously controlled melodic instruments (like the trombone or the Theremin), the *Mixing Bowl* can allow for accurate discrete pitch generation. Experienced players can locate specific pitches and velocity values within the bowl's space in order to construct a desired melody. On the other hand, the space's non-tangible, un-marked nature can also encourage players to continuously manipulate the melody contour instead of focusing on specific discrete values. The high-level contour manipulation is enhanced by the fact that the player manipulates the center pitch of an arpeggiator, whose parameters are controlled by other players. These players provide significant high-level musical parameters to the arpeggiator (such as the harmonic stability, for example) by dynamically changing its interval, scale, tempo and register. The external influences do not always allow for meaningful discrete pitch or velocity generation and can lead the bowl player to experiment with higher-level gestures.

The different levels of control also serve an important role in providing a rich environment for top-down immersive explorations as well as for bottom-up constructivism. The *Squeezable Voice Ball*, for example, is designed to allow users to construct their voice manipulation in an analytical discursive manner as well as in an expressive immersive one. On the bottom-up front, the voice ball offers several low-level effect parameters such as flange rate and depth, delay time and feedback loop. By experimenting with squeezing the different sensors, players can find the exact functionality of each gesture and construct the timbre effect. The same low-level character of these parameters can also encourage users to perceptually shift into manipulating higher-level musical aspects like "timbre color" or "*Sound Sculpture*." Manipulating low-level, non-intuitive parameters such as "feedback loop level" or "flange depth" can draw children to experiment with a top-down approach by expressively molding the ball and only gradually exploring the functionality of each gesture. The ball's irregular, non-organized sensor design enhances this perceptual shift. Although each sensor is mapped to one timbre parameter in a simple one-to-one manner, their intermingled design makes it difficult to follow the basic relationships and can encourage bricoleurs to explore a higher level of conceptual control.

The interdependent connections among the different modules/instruments are important contributors to the iterative shift between construction and immersion, which is encouraged by the system. When these connections are taken advantage of, the system's players receive partial control over their musical output. This can encourage focusing on expressive holistic musical aspects rather than specific constructive details, which can lead to an immersive experience where the user has partial, yet meaningful, control over the dynamic flow of the music. Generally, it can be claimed that the more external influence players receive on their instruments' output, the more immersed in a holistic experience they may be.

One example for such interdependent immersion is *the Squeezable Voice Ball's* and *Digital Talking Drum's* influence on the *Mixing Bowl.* The combined squeezing signal from the *Voice Ball* controls the bowl's *Arpeggiator* scale. The higher the signal is the more chromatic and less diatonic the *Arpeggiator* scale becomes. The *Arpeggiator's* width is controlled by the *Digital Talking Drum* hits' velocity - the stronger the hits are, the wider is the register in which the *Arpeggiator* plays. The *Arpeggiator's* tempo is controlled by the level of drum squeezing, which also controls the drum's delay time level. The shorter the delay time is, the faster the tempo is.

These mappings take into account the delicate balance between generating interesting interactions among the different instruments on one end and having the players lose control over their instruments on the other. It was decided to provide the *Mixing Bowl's* player with full freedom in controlling the *Arpeggiator's* volume in order allow for full control over phrasing the melody line. If other instruments were provided with the ability to manipulate this feature, the *Mixing Bowl* player would not have been able to execute her musical ideas since the causality between her gestures and the phrases' sound level would have been impaired. It was also decided that the external influence over the *Arpeggiator's* parameters would not influence the *Mixing Bowl* player's full control over the *Arpeggiator's* center point, which is crucial for controlling and perceiving the melody contour. Without full control over this feature, users could have lost the sense of the phrase height and directionality. Other *Arpeggiator's* parameters such as scale, width and tempo *are* provided with external influence since they have minor enhancing effect on the "cloud" of notes around the contour center point. The rationale was that these parameters could enhance the melody and the musical interaction without impairing the bowl player's control over the melody.

The interdependent connections that were formed between the *Digital Talking Drum* and the *Squeezable Voice Ball* exemplify how the system allows players to control the level of external influence over their own modules. As can be seen in figure 28, the squeezing data from the *Digital Talking Drum* is also sent to the *Squeezable Voice Ball* effect manipulation control. The algorithm forms a reverse relation between the *Squeezable Voice Ball* squeezing influence and the *Digital Talking Drum* squeezing influence on the processed timbre. The harder the *Squeezable Voice Ball* is squeezed, the less influential squeezing the drum becomes. This allows the *Squeezable Voice Ball* player to set the level of autonomy he receives over his own instrument's timbre. When the ball is not squeezed at all, the drum player receives full control over the ball's timbre. When the ball player decides to have more control over the timbre, he can squeeze the ball harder, which not only adds control data to the algorithm but also reduces the influence of the drum interdependent control. This functionality can provide the players with better control over their iterative transit between construction and immersion, low and high-level control, interdependency and autonomy.

3.3.2 Implementation

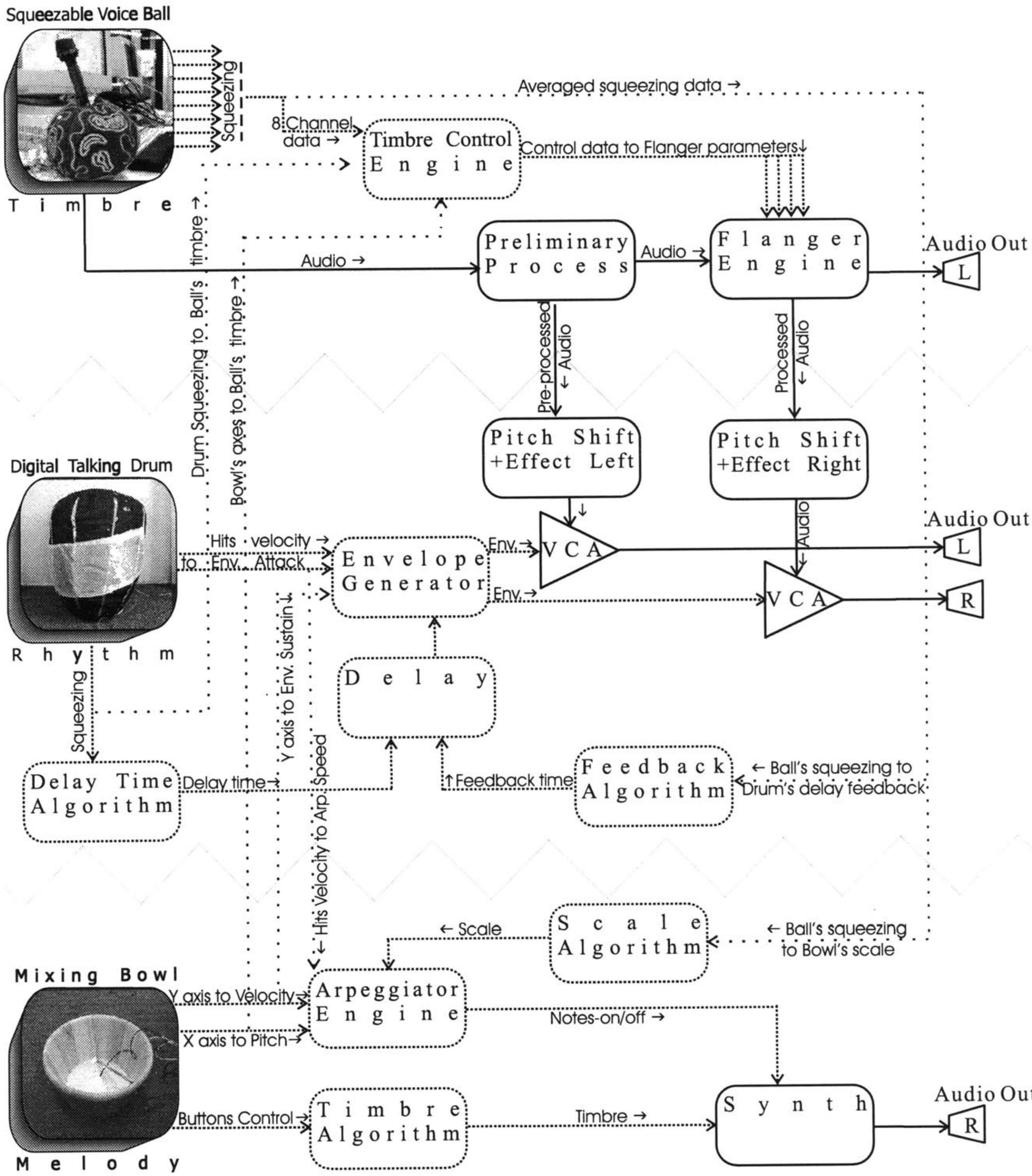

Figure 28 - The *Integrated System* Functionality Scheme

Index

Audio Data ⟶ Internal Control Data ·······> Interdependent Control Data · · · · ·>

The scheme is divided into three sections, each representing a different module/instrument - the *Squeezable Voice Ball* at the top, the *Digital Talking Drum* in the middle and the *Mixing Bowl* at the bottom. Pictures of the instruments represent the different input interfaces, which send control data (dotted chords) and audio data (solid chords) to the different control modules (dotted boxes) and audio modules (solid boxes). The interdependent data (control data which is sent from one module to control other modules) is represented by widely spaced dotted chords.

3.3.2.1 The Squeezable Voice Ball

The *Squeezable Voice Ball* (coding by David Lowenfeld) serves as the *Integrated System*'s timbre manipulator. It enhances the functionality of the previous squeezable interfaces by allowing users to manipulate their own voice. The instrument is based on the assumption that children would find manipulating a familiar, personal sound like their own voice more expressive than playing with generic prerecorded timbres.

The ball receives audio data and control data. The audio is captured by a microphone that is embedded inside the ball. Control data is captured by eight conductive fabric electrodes, which are embroidered around the ball's circumference. The fabric electrodes (developed by Maggie Orth and Remi Post [Orth 1998]) provide continuous data, which represents the pressure level exerted on each electrode. Pressing the electrodes by squeezing the ball manipulates a number of audio effect parameters on the voice timbre.

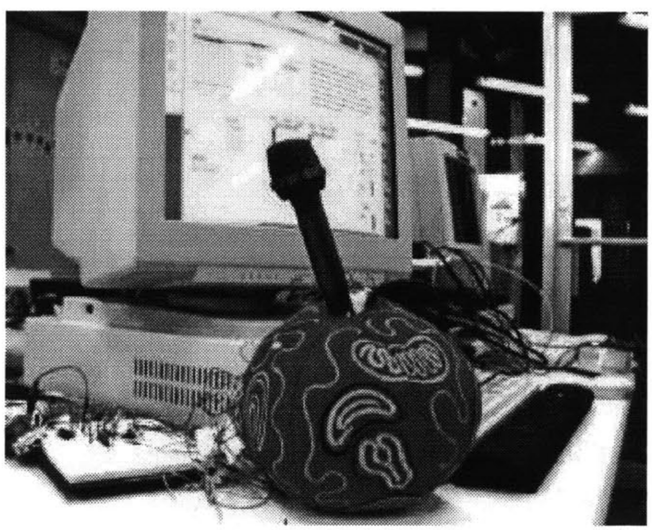

Figure 29 - The *Squeezable Voice Ball*

The voice signal is initially treated by a compressor, an equalizer and a gate in order to enhance the sound quality. It is then sent to two different channels: The "Pre-Processed Audio" channel is pitch shifted and sent out to be triggered by the *Digital Talking Drum*'s left pad. The second "Processed" channel is sent through additional flanger sound effect (using Max MSP – a digital signal processing module of Max, and a Lexicon LXP-15 effect box). The signal is then sent to the speakers as well as to the *Digital Talking Drum*, to be triggered by hitting its right pad. The continuous squeezing data (sensed by the eight fabric electrodes) is averaged into four channels, which manipulate the four interdependent flange effect parameters on the processed audio channel. The parameters are flange rate and depth, delay time and feedback loop. The squeezing control data is also sent to manipulate a number of musical parameters of the *Digital Talking Drum* and the *Mixing Bowl*. In return, data from these two instruments is sent back to the *Squeezable Voice Ball* to further manipulate the effect parameters (see figure 28).

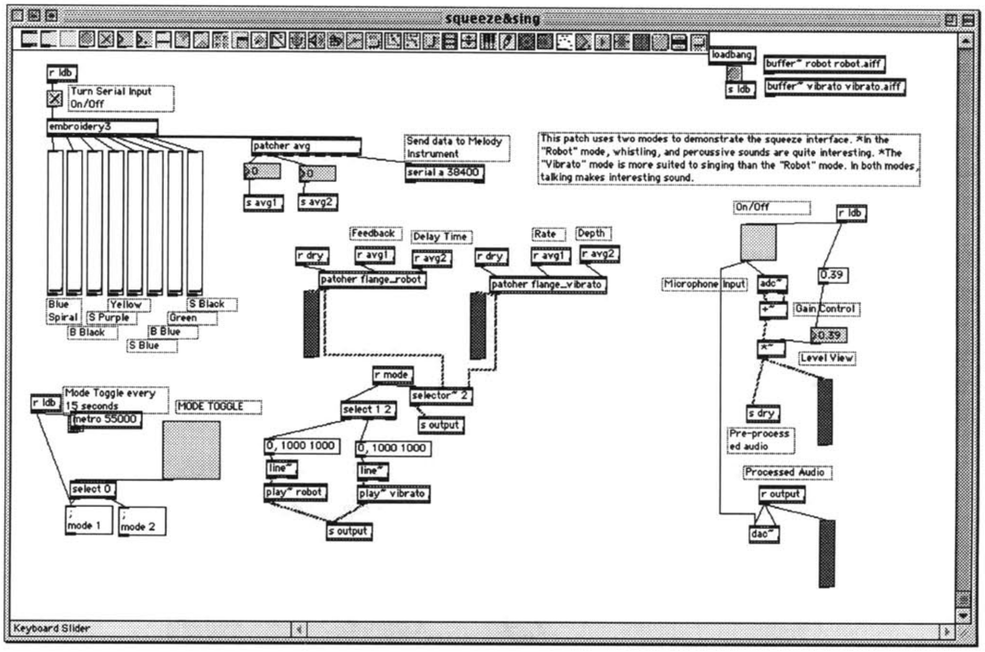

Figure 30 - The *Squeezable Voice Ball* Max Patch

The eight squeezing channels are captured and parsed by the "embroidery3" object on the upper left side. They are then sent to eight "fader" objects, one for each sensor, for visual representation. The data is averaged by the "avg" patch and then sent to two effect patches – "flange_robot" and "flange_vibrato." In these patches the averaged audio data from the microphone (received through the "adc~" object on the middle right side) manipulates the flange rate, depth, delay and feedback of the streaming audio. A toggle switch on the lower left side allows the user to choose one of two effect setups.

3.3.2.2 The Digital Talking Drum

The *Digital Talking Drum* (coding by Seth Bisen-Hersh) serves as the *Integrated System*'s rhythmic module. It is inspired by acoustic African "talking drums," where continuous squeezing gestures control the drum's cavity size and shape, and as a result, manipulate the instrument's timbre and frequency. Hitting the *Digital Talking Drum* is sensed by two piezo electric plates that are mounted on the drumhead. The two sensors divide the drumhead into two separate sensitive regions, left and right. Squeezing the drum between the player's legs is sensed by a conductive fabric wrap that is embroidered around the drum's body.

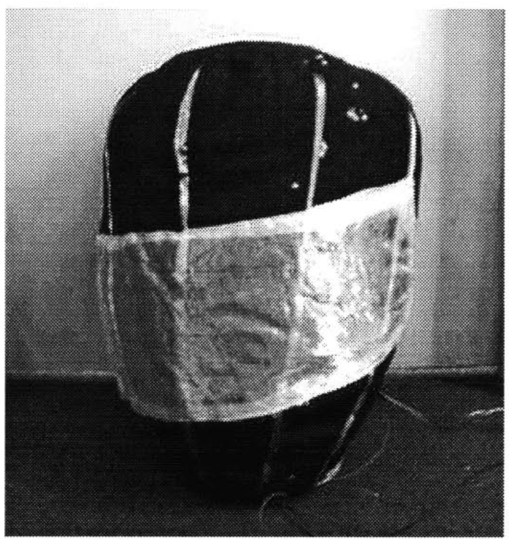

Figure 31 - The *Digital Talking Drum*

The drum receives its timbre from the *Squeezable Voice Ball* in two different channels: pre-processed signal and processed signal. The continuous audio data in both channels is trimmed into a percussive sound by an envelope generator and an effect unit. The envelope parameters include Attack Level, Attack Time, Decay Time, Sustain Level and Release Time. The effect unit shifts the pitch down by two octaves and adds reverberation. The envelope generator and effect parameters are manipulated by the other two modules/instruments (which are manipulated by the squeezing control from the drum in an interdependent loop - see figure 28).

The pre-processed channel is triggered (as a short percussive sound) by hitting the left side of the drumhead while the second processed channel is triggered by hitting the right side. Hits' velocity are mapped to control the drum volume level. A delay engine is applied with every hit and is controlled by the hit velocity as well as by other parameters from the *Squeezable Voice Ball* and the *Mixing Bowl*. The audio is then sent through a voltage control amplifier and a maximizer effect to a pair of speakers.

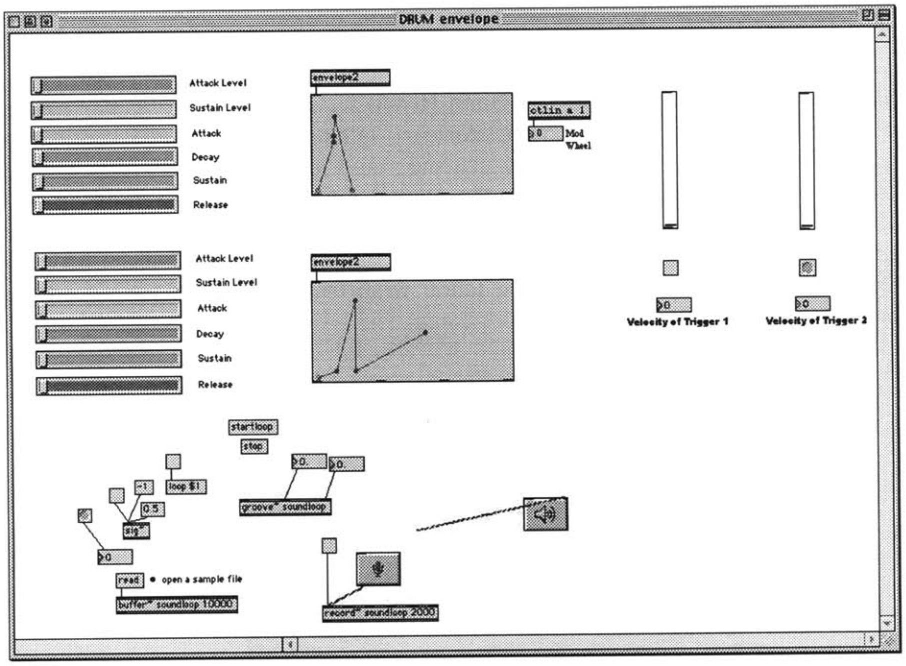

Figure 32 - The *Digital Talking Drum* Max Patch

Five faders for each envelope parameter are assigned to each audio channel and control the graphical envelope representation in the center. The "envelope2" "groove~" and "buffer~" objects control the system's inputs and outputs.

3.3.2.3 The Mixing Bowl

The *Mixing Bowl* serves as the *Integrated System*'s melody instrument. The Bowl uses the FISH sensor (developed by Josh Smith [Smith 1998]) to sense the electric field of the player's hand inside the bowl. Hand's proximity to the bowl's circumference is captured and the data is mapped to control the pitch and velocity of an *Arpeggiator*'s engine. The metaphor of "mixing" was chosen so that the player will be encouraged to "stir" the notes in the bowl in order to create the melodic phrases.

The bowl is divided by two axes: the left-to-right X-axis and the bottom-to-top Y-axis. The X-axis is mapped to channel volume, which allows the player to create musical phrases by controlling the melody volume contour. The Y-axis is mapped to control an *Arpeggiator* engine's pitch center-point. The *Arpeggiator* receives its width and speed parameters from the *Digital Talking Drum* and its scale and intervals from the *Squeezable Voice Ball*. The bowl player can manipulate the *Arpeggiator*'s center pitch, which controls the core of the melody contour. A five-button control panel provides a discrete mechanism to choose different program changes that control the melody's timbre. Based on the *Arpeggiator* algorithm, a list of Midi note-on and note-off commands is sent to a Roland SC-55 Canvas play-back sampler which also receives the discrete timbre commands from the button-based control panel. The audio is then sent through an amplifier to a pair of speakers.

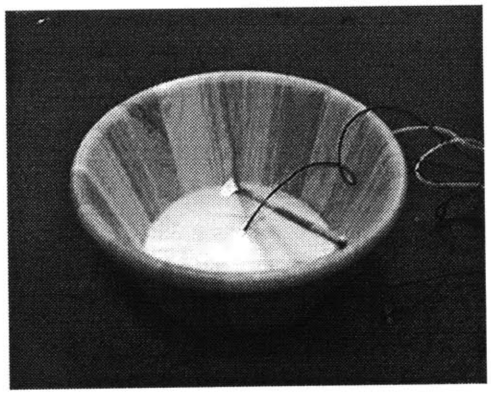

Figure 33 - The *Mixing Bowl*

Two main Max Patches control the *Mixing Bowl*. They are described below:

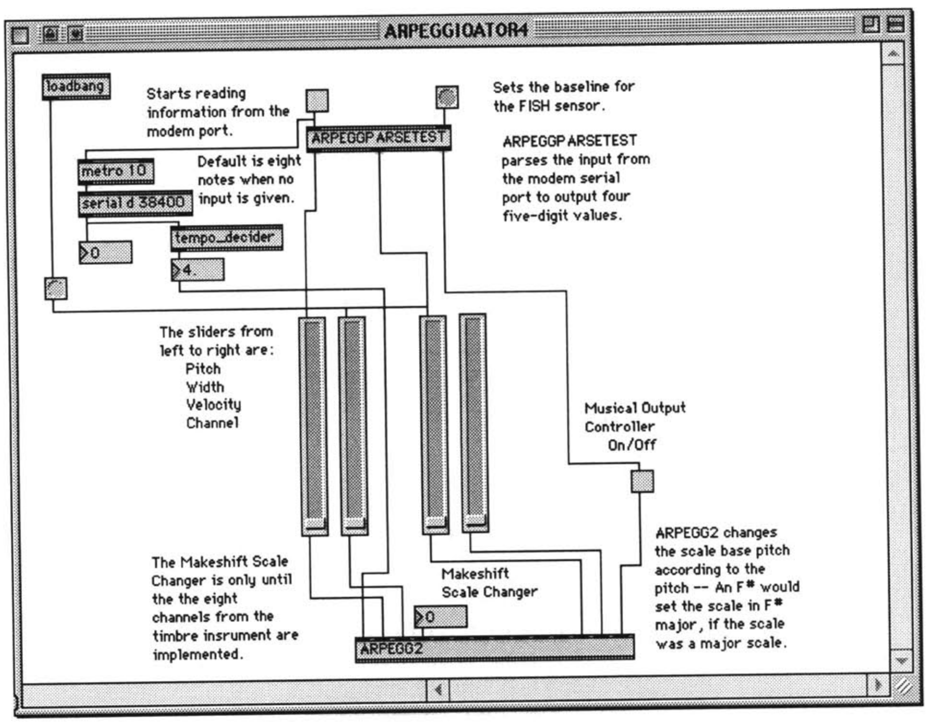

Figure 34 - The *Mixing Bowl* main Max Patch

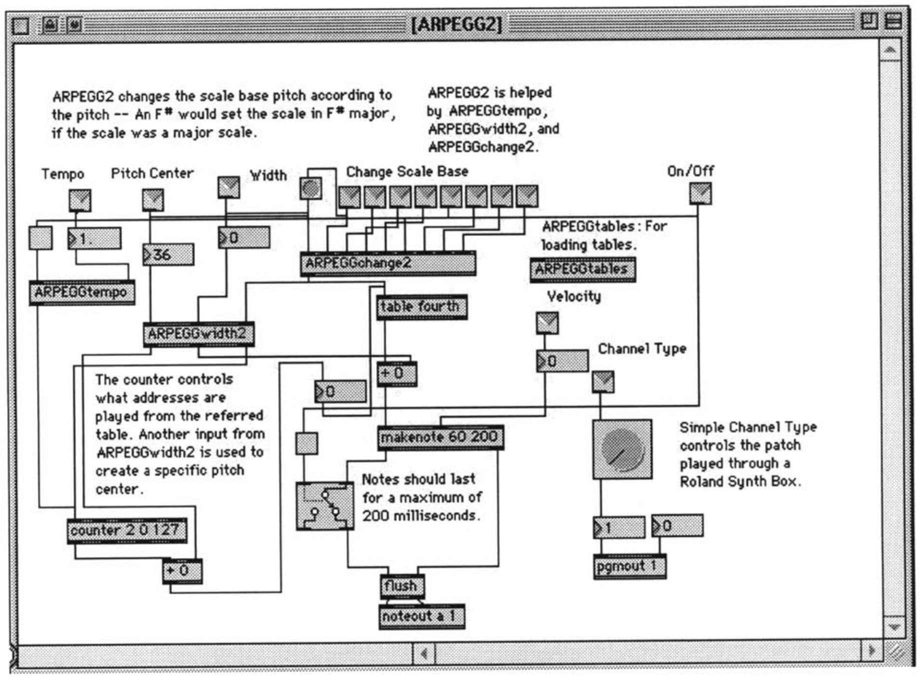

Figure 35 - The *Mixing Bowl*'s ARPEGG2 sub patch

3.3.3 Evaluation

Although the *Integrated System* succeeded in providing an open-ended, flexible, and at times even "transitional" musical environment, it also suffered from a number of substantial imperfections that were mostly derived from the system's software and hardware limitations. The system was based on a Macintosh G3 300 Mhz computer running Max MSP (Max audio processing module) and a Midi synthesizer. This architecture could not provide sufficient latency values and computation power for smooth and responsive operation.

For example, due to the slow processing and the limited MSP resources, the *Squeezable Voice Ball's* eight channels of continuous data had to be averaged to control only four flanger parameters in two different modes. These limitations impaired the ability to manipulate the player's voice in interesting and rich manners, which lead to narrow musical outcome. The lack of additional high quality recording equipment such as compressors, limiters and effects processors also contributed to the system's poor sound quality, which did not allow for delicate manipulations of the ball to be audibly noticeable.

The high latency drawback (more than 30 msc. from triggering a sound until playing it back) was especially noticeable in the *Digital Talking Drum*. Like most percussive instruments, the *Digital Talking Drum* requires short latency values (less the 10 msc.) in order to convey a fast and responsive drumming effect (imagine hitting a drum and hearing its sound only a while later). This problem made it very difficult for the drummer to generate accurate beats and interesting rhythmical patterns. The drum also could not effectively utilize the *Squeezable Voice Ball's* timbre, from which it received its input. It was found out that continuous human voice timbre is not an optimal source material for creating persuasive percussive sounds. Although it was pitch shifted, enveloped and manipulated bye effect processors, the drum sound was not distinguish enough from *Squeezable Voice Ball* sound and could not effectively support the systems' rhythmic section.

The *Mixing Bowl* was probably the most successful module in the system. The bowl received significant interdependent data from the *Squeezable Voice Ball* into its *Arpeggiator* scale algorithm, which provided the bowl's player with a dynamic and interesting musical melody phrasing mechanism. However, due to the *Digital Talking Drum's* latency shortcomings, it was very difficult for the drum player to send coherent and rhythmical tempo values to the bowl's *Arpeggiator*. As a result the *Arpeggiator* tempo suffered form jerkiness and unintended inconsistencies, which made it somewhat difficult to control.

The above deficiencies prevented a deep examination of the conceptual musical axes implementation since the system did not operate entirely as was expected. I believe that improving the *Integrated System* computation power, latency and the recording-equipment quality can lead to a successful fully operational apparatus, which could then be subjected to a full musical evaluation.

4 OBSERVATIONS AND REFLECTION

I will here describe a number of observation and reflection sessions that were conducted with children and adults. These observations serve as representative case studies and do not attempt to provide well-controlled statistical results. Some of the instruments (such as the *Integrated System*) are not reviewed in this section due to thesis deadline limitations. Other instruments (like the Immersive Interfaces) can only allow for observations and not reflection sessions due to the participant's young age (1-2 years old). The three instruments that will be included in this section are *Squeezable Cluster*, the *Musical Playpen* and the *Scaleshipss*. They were chosen due to the full representation they can offer of the different concepts that were discussed in this thesis: Observations and interviews with a *Squeezable Cluster* players will concentrate on high and low control levels; Observations of a the *Musical Playpen* users will focus on the tension between immersion and construction and a self reflection of playing with the *Table of Squeezables* will address the issues of interdependency and autonomy.

4.1 The Squeezable Cluster

The two applications that were developed for the *Squeezable Cluster* focus on manipulating different levels of musical "building blocks". The Sound-Sculpting application allows children to construct the character of a sound by manipulating low-level timbre parameters such as filter, resonance, FM, etc. The *Arpeggiator* application encourages the manipulation of high-level interdependent sequence parameters like level of "chromatisim", the melodic range or the level of accentuation. Although both instruments can be played in various manners, I anticipated that professional musicians would find interest in the *Sound Sculpture* application due to its accuracy and repeatability. I expected children and novices to enjoy the *Arpeggiator* application due to its playful and expressive nature as well as its immediacy, which does not require musical knowledge or a long practice period in order to produce compelling musical results.

Jill[2], a 7-year-old with little musical experience, was a little confused when she was asked to play the *Arpeggiator* application without any guidance. She held the *Squeezable Cluster* in her hands for a while, tried to understand its functionality and almost got bored when she suddenly squeezed it unintentionally and played a short sequence of notes. She became very interested, brought the Squeezable close to her face and tested it ball-by-ball, trying to isolate each ball's influence on the music. She was frustrated we she realized how difficult it was in this particular application. I asked her what she was doing:

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[2] All names have been changed in order to respect interviewees' privacy

Jill:	*That's very cool; I'm trying to understand now how it works.*
Question:	*And what did you discover?*
Jill:	*It is very hard; I cannot understand what every ball is doing.*
Question:	*Why don't you just play? You said it was cool.*
Jill:	*First I want to understand how it works. Then I'll play.*

Jill could not get herself to enjoy the complex, high-level experience without exploring first the instrument's low-level building blocks. She did not let herself to be immersed in the music but had to understand what was the mechanism behind the instrument. It seems that at this point she preferred the analytical approach on the experiential one, so I changed the setup to the *Sound Sculpture* application, which is easier to control in a analytical manner due to the one-to-one mapping scheme. Jill repeated the process of detailed exploration of every ball's role. This time she looked even more content:

Jill:	*That's even cooler...it sounds better....*
Question:	*Why?*
Jill:	*I can control the noise.*
Question:	*Can you make it less noisy and more musical?*
Jill:	*Sure, you see, this ball controls how fast it goes.*

Jill was very tensed and concentrated when she tried to isolate the gesture that is responsible for manipulating the LFO.

Question:	*Are you having fun, it seems that you are very concentrated?*
Jill:	*Yes, I'm learning it.*
Question:	*Is it harder or easier then the Arpeggiator ?*
Jill:	*... The Arpeggiator was fun to play but it was hard to repeat things that you liked. Now it is easy to repeat things that you like but it is harder to play.*
Question:	*What do you mean by harder to play?*
Jill:	*It doesn't help you. You have to do everything by yourself.*

Jill considered the algorithmic *Arpeggiator* as "help" provided for her by the computer. She also considered the accurate control in the *Sound Sculpture* application as more demanding and "harder to play," ignoring the fact that she quit her attempt to analyze the *Arpeggiator* after a while.

Question:	*Wasn't it difficult when you couldn't repeat exactly what you did in the Arpeggiator ?*

Jill did not reply but asked me to switch back to the *Arpeggiator* application. She played it for a while, this time in a much more expressive and free manner. She seemed to have fun.

Jill: *You know what, it is much more fun now when I know that it is not accurate. I think I like this one best.*

Even though Jill did not relate to the *Arpeggiator* immediately, she learned to like it and to control it more expressively. The instruments allowed her to develop play patterns over time.

A different angle on the subjects was presented by Kristian, a 60-year-old musically trained technical manager, who was invited to play with the *Squeezable Cluster*. Kristian was visiting the Media Lab as a sponsor during the 1997 fall Open House. Unlike Jill, his response to the *Arpeggiator* was immediate [Weinberg 1999]:

Kristian: *It is great... just great (laughing loudly).*
Question: *What is great about it?*
Kristian: *(Moving his body expressively.) You make me feel like a composer....*

I changed the setup to the *Sound Sculpture* application. Kristian was surprised to hear the new sound, but after a while, he started twisting his body while playing expressively:

Question: *So what do you think about this one?*
Kristian: *(Stopped laughing) ....I hurt the little guy.*
Question: *(Thinking he meant that he was damaging the object.) That's O.K – it is strong enough.*
Kristian: *No, I mean it sounds as if it is in pain...listen to it crying....*

The 60-year-old senior technical manager was completely immersed in the experience. He didn't want to explore or to understand how the *Squeezable Cluster* worked. Not only did he regard the instrument as alive, he showed feelings of compassion towards it. Kristian definitely presented immersive high-level play patterns. His expressive uneducated attitude towards playing the instrument was completely different from Jill's analytical exploratory approach. I expressed my surprise that Kristian, who came from an analytical and musical background, did not find interest in the sensing mechanism or the mappings:

Kristian: *Now that you mentioned it, yes I am interested – what kind of sensors did you use?*
Question: *Force Resistor Sensors. Weren't you interested in that when you were playing?*
Kristian: *No...then it would have ruined the magic.*

While Jill regarded playing the *Squeezable Cluster* mostly as an analytical exploration, Kristian saw it as magic. While Jill could not start playing without clearing the opacity from the instrument's functionality, Kristian used this opacity to reach new forms of expressivity. I believe that if more time was given to these observations, both subjects would have shown some transitional movement towards the other ends of the control-level axis.

4.2 The Musical Playpen

The playpen was designed to encourage children to participate in top-down immersive musical experiences. Its immediate responsiveness and its tendency to arouse tempestuous play gestures suggested that children would start their experience in an immersive holistic way and gradually expand towards lower-level exploration. However, the observations that were conducted at MIT and at the Boston Children's Museum from 1998 to 1999 [Weinberg 1999] have shown greater diversity in the response of children to the new instrument. For example, one 1-year-old infant started her session with a careful investigation of the different corners' functionality. The first sequence of notes that she "played" was generated when she was placed near an Indian-Rag corner. The infant looked at the direction of the sound source (the speakers were hidden under the balls in the playpen) and tried to move her hand in that direction, seemingly trying to repeat the sound she heard. When she succeeded and another sequence was played, she smiled, took one ball and tried to shake it in her hand, obviously without success. Frustrated, she then threw the ball back towards another corner, generating a different percussive sequence. She approached the new corner while moving her torso back and forth; laughing loudly when she found out that her movements controlled the music. After stopping for a while, as if she was considering her next move, the infant started to move her body again, very slowly, back and forth. Gradually her movements became faster, generating higher and higher percussive frequencies. She then stopped abruptly and waited, maybe processing the new connections that she found. Only after repeating this behavior in another corner, did the infant seem to be ready to use more expressive, less controlled gestures all over the playpen. She now seemed to have fun.

This bottom-up, almost analytical, constructive approach did not repeat itself with another 16-month-old toddler. The first play patterns that were demonstrated by him were turbulent movements all over the playpen, kicking and waving his arms, throwing balls all over and accompanying himself by singing and screaming joyfully. This random activity was very exciting for a while and he did not allow anyone to stop him or take him out. After this expressive explosion, the toddler started exploring the different responses in the different corners around the playpen. He then performed several abrupt jumps from one corner to another. Towards the end of the observation, the toddler seemed to have developed unique play patterns and a personal musical tendency: his "compositions" included ecstatic random parts in the center of the playpen which were interrupted by gentle exploratory parts near the different corners. In a controlled environment, where he was placed in a playpen that was disconnected from its musical output, no organized play patterns were observed.

The above observations exemplify the diversity in children's response to the playpen. Some players preferred staying in the immersive stage and its expressive, holistic, sometimes ecstatic nature. Others concentrated on an analytical exploration process of the low-level musical parameters that construct a full musical experience. In several observations the playpen managed to be successful in encouraging children to develop their play patterns over time and go through a "transitional process". A number of 'bottomuppers' were able to elevate themselves towards new immersive realms. A number of 'top-downers' also managed to 'dive' down and explore lower-level musical aspects. The above findings suggest that players' tendencies and personal play patterns serve an important role in defining the immersive (or constructive) nature of the musical experience. Even in an instrument like the playpen, which was designed to be played in a top-down immersive manner, a 'constructivist' player will be able to find the low-level musical building blocks first and then construct them into a full musical experience.

Another observed aspect was the effect of group interdependency on children's play patterns. The playpen was not initially designed for group playing and no interdependent software connections were embedded in it's mapping. However, the instrument did provide physical interdependency, where children's gestures in specific corners propagated through the balls toward other corners and triggered sequences that were more often controlled by other children in the playpen. The observations showed that the play patterns which were presented by several groups of three and four children did not develop towards lower or higher levels. Most of the children seemed to stay in a high-level immersive state, which included random jumps and non-organized ball throwing. The playtime in this multi-user setting was usually shorter than in the individual setting and children seemed to get bored more rapidly. I tend to explain these findings by the uncontrolled nature of the physical interdependency, which often did not allow for a minimum level of control that is needed for a meaningful musical experience.

4.3 The Table of Squeezables

In this section I evaluate the *Table of Squeezables* and reflect on the experience of playing it from the point of view of a musician (myself) rather than a child. Such a reflection can demonstrate how the instrument addresses professionals as well as novices by offering a varied range of musical challenges for players with diverse musical background.

The instrument's heterogeneous nature was designed in an effort to provide different users with different musical activities in varied levels of interdependency. The melody ball for example, receives the highest level of interdependent input and is capable of controlling some interdependent aspects in the other balls. The accompaniment balls on the other hand, receives little interdependent input but their output can contribute substantially to the melody ball's algorithm. As the application's designer I was often assigned to play the melody ball since I was familiar with its algorithmic details and could supposedly manage its multiple interdependent input channels. However, it had taken a decent number of rehearsals before I began to gain control over the scale, level and pan values that were "thrown at me" by the other players. It was even more difficult to incorporate these parameters into my melody contour in a coherent musical manner. The dynamic flow of such significant musical parameters into my music required high level of concentration and left me in constant state of trying to expect the unexpected. Unlike playing a traditional instrument, controlling my musical output was *not* only up to me. This occasionally led to the impression that I was not playing the instrument; rather the instrument (or the other players) was (were) playing me. At times, when the other players were particularly experienced and skillful, playing the melody ball felt almost like controlling an entity that has a life of its own.

My impression was completely different when I was experimenting with the accompaniment balls. Here, I was able to influence the melody ball player without being significantly influenced by myself. However, I could not do it alone. I had to collaborate with the other accompaniment balls players in order to substantially influence the melody since the melody's algorithm used the signal sum from the five accompaniment balls, and not their individual signal. Similarly to chamber music group interactions, body and facial gestures had to serve an important role in establishing a collaboration that would considerably influence the melody. These familiar personal interactions in addition to the autonomous nature of accompaniment balls also turned out to be especially compelling for children, who found the accompaniment balls intuitive and easy to play with.

While helping in the formulation of an intermediate, transitional, balance between autonomy and interdependency, the strict division to accompaniment and melody also bears several disadvantages. Most of the children who played the instrument chose not to play the melody ball due to its complexity and inconsistency. On the other hand, many musicians (myself included) found the accompaniment balls too autonomous and restricting. Often, these balls did not provide the new exciting features that are affiliated with higher levels of interdependency. (As a result, a better-balanced interdependency implementation was developed for the *Integrated System*.)

Another problematic feature in the *Table of Squeezables* was the lack of individual personalized interdependent connections among specific accompaniment balls and the melody ball. Although this feature *did* encourage group playing, it also blurred the relationship between individual accompaniment players and the melody soloist. As an accompaniment ball player, I was not provided with the ability to take individual choices concerning the melody, without coordinating these decisions with the rest of the group. This difficulty could have been addressed by a mechanism that allows the accompaniment balls players to set the level of their individual influence on the melody in real time. Such functionality could have also been helpful to the creation of a dynamic "social musical system" where players set their own preferred level of influence. This could have allowed players to choose (while playing) whether they want to serve as small elements in a larger entity or whether they prefer to take their own individual musical track and step out of the collaborative.

An important feature for creating such a "social system" is the choice of musical parameters that would be subjected to external influence, as opposed to those who stay internal within the instrument. For the melody ball it was decided to allow external manipulation of the scale, velocity and pan values while leaving an autonomous control over the melody contour and timbre. These choices led to some absurdities that impaired the musical interaction. For example, allowing the accompaniment balls to control the melody's velocity values (which also effect the track's volume) led to occasional silencing of the melody channel. In such cases the melody player's gesture became irrelevant. The *Integrated System* design fixed this problem by leaving the melody volume contour as an internal parameter, which led to a better sense of control and to more meaningful musical phrasing process.

Another problematic mapping choice in the *Table of Squeezables* was leaving the timbre as an autonomous internal parameter. I now believe that timbre is an appropriate candidate for external control, since it does not affect fundamental musical parameters (such as pitch, rhythm and velocity) but creates a subtle effect of "coloring" the melody without changing its core features. This can enhance the melody's interdependent richness without impairing the player's control.

5 FUTURE WORK

A varied range of future research can emerge from the work on expressive digital musical instruments for children. I intend to improve the instruments' sensing technology as well as to further explore theories of expression, emotions and technology. The concept of interdependent musical interactions is also a research direction that I would like to further develop. I hope to create large interdependent musical networks that include dozens of interconnected instruments. And lastly, some of the instruments that I developed turned out to be especially interesting for people with various disabilities. I intend to steer my research into issues in design of musical instruments with artistic as well as therapeutic values for the handicapped.

5.1 Technical Sensing Improvements

One of the immediate required improvements is to enhance the accuracy and reliability of the sensors in several of the instruments that were discussed above. For example, the *Musical Playpen's* piezo-electric sensors do not provide a wide signal range for sensing delicate children's movement around the playpen. In order to be able to accurately control the melody and drum contours, other sensors should be tested. First experiments have been made with commercial accelerometers and pressure sensing strips. I hope that these sensors will also be useful for sensing children's movement trajectory, using higher levels of spatial resolution. This will enable mapping children's gestures to more interesting musical parameters, since the pitch and volume contours seem to be limited after a while, as they did not provide the depth that was required by some of the more musical children.

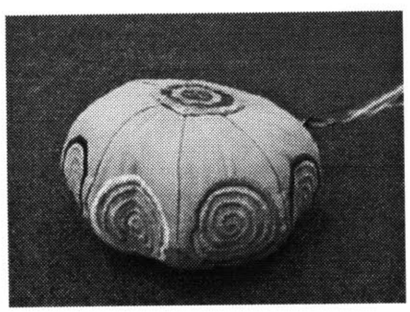

Figure 36 - The Conductive Fabric "Pumpkin"

Another group of instruments that should be improved in terms of sensing reliability is the *Squeezables*. The FSR pressure sensors that were used in these instruments tended to break and did not always provide a reliable signal. The conductive fabric sensors that were used in the *Squeezable Voice Ball* presented better robustness and durability, but their accuracy was limited, as well as their multiple-sensor operation capabilities. First efforts have been made in order to improve the conductive sensor's responsiveness in the Conductive Fabric "Pumpkin." The first prototype has eight fabric electrodes, which are mapped to control pre-recorded musical sequences. The continuous signal from the sensors is currently mapped to the timbre and volume level of the pre-recorded tracks.

5.2 Affective Computing

This thesis started with a review of several musical expression theories, some of which tried to form direct relations between low-level musical parameters, such as an interval, and specific emotions, such as restlessness. Although I do not believe that these kinds of connections can be valid or effective globally, I do believe that further research in the area of emotions, music and technology should be done in order to be able to provide new ways of expression in musical instruments. The Affective Computing group at the Media Lab has conducted some preliminary research in this area. The group hopes to develop computer programs that can sense, and maybe even express, emotions [Picard 1999]. I intend to study this direction of research (keeping a skeptical mind) in order to find new ways to enhance the expressive interaction that digital musical instruments will be able to offer in the future.

5.3 Wireless Musical Networks

An exciting line of research that evolved from the *SqueezMan* project is the development of large networks of wireless musical instruments. Due to the large numbers of instruments in such networks, each instruments' functionality can be very simple when it is played in a stand-alone mode. The instruments' interesting, more complex, behavior can emerge when they communicate with a large number of similar units. The musical simplicity is especially important in multiple-player mode when dozens of players interact simultaneously, each trying to control and follow his/her personal contribution to the whole. The interdependent connections among such a large number of instruments should be designed carefully in order to allow for interesting interactions while providing players with enough control over their instruments. One of the interesting challenges in developing such a system is to locate the right balances, which allow players in the stand-alone mode to have a meaningful enough interaction in spite of the simplicity of operation.

A prototype for a large interdependent musical system, the *Musical Fireflies*, was developed with Jason Jay and Tamara Lackner [Jay 1999]. The *Musical Fireflies* are digital rhythm toys that network through infrared communication. They allow children to enter drum patterns by tapping in drum patterns, embellish them in real-time, synchronize with each other and then play together by trading back and forth the instrument sounds. Using only two buttons, one for accented notes and the other for non-accented notes, children can record complex rhythms and synchronize with their peers while generating poly rhythmic patterns. The *Fireflies* also provide an educational value where the players can learn and internalize musical concepts as well as mathematical concepts. For example, when one *Firefly* plays a 4 beat pattern and another plays a 7 beat pattern, users can hear the process of divergence and convergence, as the patterns go in and out of phase every 28 beats. Such processes can encourage children to experiment with different combinations of rhythmic patterns in order to explore how multiplicative relationships emerge. Trading their timbre with friends can provide children with a simple enough interaction that can be followed and controlled even in a larger group. However, this simple discrete interaction does not allow for a deep meaningful musical activity. Further development of such a system should include continues interactions that involve different musical parameters and more interesting connections (like musical challenge games for example). We hope that such a musical network can serve an important role in the "Toy Symphony" [Machover 1999], which is planned to premiere in 2001.

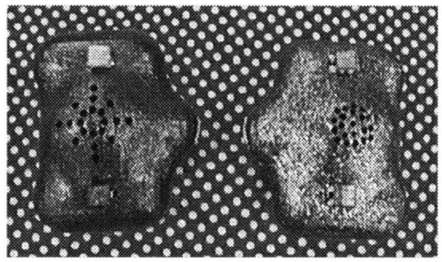

Figure 37 - Two Musical Fireflies

5.4 Musical Instruments for People with Disabilities

During the development of the different projects that are discussed above, I was approached by several individuals who were interested in appropriating the instruments for the use of people with disabilities. Apparently, the instruments' tactile and intuitive nature seemed to be compelling for those whose normal senses' operation was impaired. In one case I was approached by an acquaintance of a car accident victim who lost almost all control over his body. The accident left him unable to move, speak or operate in any functional way and apparently also impaired his mental ability. After a series of medical operations he was provided with some limited control over his right thumb in addition to some control that he had already gained over his facial and neck muscles.

The main action that the car accident victim was able to perform (with seemingly a lot of effort) was a very weak movement of bringing the thumb a little closer to the rest of his palm. He was also capable of communicating his satisfaction or dissatisfaction by manipulating his facial and neck muscles. Since he was a music lover before the accident, his acquaintance wanted him to be able control some music by using the only gesture at his disposal. After learning his case, Sem Lim Gan and myself built a very simple squeezable device that he could press with his thumb in order to hear a simple tone in response. The satisfaction he managed to express by moving his facial muscles when he succeeded in playing the tone was exciting and moving. It encouraged me to look deeper into building instruments that can help people in such conditions to express themselves with music.

Another moving inquiry for using a digital musical instrument came from a blind 12-year-old who wanted to play music but found it very difficult to practice any traditional instrument. She was especially interested in the playpen since she liked the medium and felt that her lack of vision would not impair the experience. Due to technical and distance circumstances I was not able to provide her with the experience that she wanted. However, these kinds of inquiries present a whole new research direction that can be contributing and meaningful. I intend to learn more about different disabilities that can be addressed by expressive digital musical instruments. I will then try to develop appropriate instruments that will be able to help these different groups of people, which are usually deprived of any performance-based musical experience, to enjoy the expressivity and creativity of playing musical instruments.

6 CONCLUSION

This thesis is about balances. The instruments that are described in the thesis attempt to formulate equilibrium among different interconnected conceptual axes in an effort to help children to experiment with new realms of expression and creativity. The role of digital technology is central to the formulation of such equilibrium. The ability to fine-tune, personalize and reprogram the instruments emancipates the designer, and the users, from the instruments' physical limitations and allows both designers and users to customize their own preferred musical balances.

The digital musical instruments that were developed in the framework of this thesis bear the promise of allowing children to express themselves through music by means of higher-level emotional conceptualizations. Such instruments can enter and change the way in which novices and professionals perceive and relate to music: A digital instrument can have a "life of its own," which can help it "play the user" on occasions. A musical system can generate a "social tension" between individuals and a group and encourage the player to solve this tension. An immersive environment can "embrace" infants and allow them to construct or deconstructed their experiences. Interdependent musical connections can lead to new ways of thinking about the collaboration between people and musical instruments. All of these experiences can bring a new perspective to the way in which we perceive, create and perform music. Some can even provide certain groups (like infants or people with disabilities) with their very first - and sometimes only - active musical participation.

This thesis also addresses a number of future educational and symbolic goals that can be achieved by digital musical instruments. As I have shown, the customization flexibility in some of the instruments can address the issue of bridging the gap between the figural and formal modes. Other instruments led to preliminary research in the area of simulating "generic" musical elements such as "contour" and "stability". I believe that further study of cognitive development and "culture-biased" vs. "universal" musical expression can lead to an exciting line of research and interesting insights on human nature.

While opening a new world of possibilities for the creation of new and meaningful artistic experiences, the use of digital technology also bears the risk of providing too much freedom, both for designers and users. For the designer, the liberty to map any kind of human gesture to any kind of musical output can many times lead to fruitless and non-musical results. A number of applications that were developed for the digital musical instruments during the last couple of years did not find their way into this thesis due to such malpractice. Observations also showed that too much musical freedom might impair users' interaction. As an instrument designer, I had to carefully confine the range of musical possibilities offered to the players, since posing constrains turned out to be an important trigger for creative exploration. When facing open-ended applications with little restricted guidelines, many children seemed to be paralyzed in front of the abundance of musical directions and tended to loose their creative urge. On the other hand, extreme restrictions led to a similar effect of impairing creativity on the part of the players. In this thesis, which *is* about balances, finding a productive equilibrium on this "Creativity Axis" played an important role behind the designing and the development scenes.

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