Gil Weinberg
Music Department
Georgia Institute of Technology
840 McMillan St.
Atlanta, Georgia 30332 USA
gilwein@cc.gatech.edu

Interconnected Musical Networks: Toward a Theoretical Framework

This article attempts to define and classify the aesthetic and technical principles of interconnected musical networks. It presents an historical overview of technological innovations that were instrumental for the development of the field and discusses a number of paradigmatic musical networks that are based on these technologies. A classification of online and local-area musical networks then leads to an attempt to define a taxonomical and theoretical framework for musical interconnectivity, addressing goals and motivations, social organizations and perspectives, network architectures and topologies, and musical content and control. The article concludes with a number of design suggestions for the development of effective interconnected musical networks.

Interdependent Music Performance

Music performance is an interdependent art form. Musicians' real-time gestures are constantly influenced by the music they hear, which are reciprocally influenced by their own actions. In group playing, the interdependent effect bears unique social consequences such as the formulation of leaders and followers or changes in individual players' dynamics and timing in correlation to group synchronization (Rasch 1988). Other manifestations of interdependent group routines can be found in a variety of musical genres such as Western chamber music, Jazz, Gamelan, Persian music, and others (see details in Weinberg 2002). Performers often address the importance of interdependent group collaboration and sharing in their music. Jazz performer Milt Hinton noted, "I was pretty young when I realized that music involved more than playing an instrument; it's really about cohesiveness and sharing . . . I've always believed you don't truly know something yourself until you can take it from your mind and put it in someone else's" (Hinton and Morgenstern 1988). Cognitive scientists, on the other hand, tend to address the perceptual aspects of interdependent group play. William Benzon (2001) discusses his experience playing Ghanaian Bells in a group of four: "melodies would emerge that no one was playing . . . it arose from cohesions in the shifting patterns of tone played by the ensemble. . . . Occasionally, something quite remarkable would happen. When we were really locked together in animated playing, we could hear relatively high-pitched tones that no one was playing." Benzon uses this example to strengthen his definition of music as "a medium though which individual brains are coupled together in shared activity."

But although acoustic-interdependent models provide an infrastructure for a variety of approaches for interconnections and interdependencies among players, they do not allow for actual manipulation and control of each other's explicit musical voices. Only by constructing electronic (or mechanical) communication channels among players can participants take an active role in determining and influencing not only their own musical output but also that of their peers. For example, consider a player who, while controlling the pitch of his or her own instrument, continuously manipulates the timbre of a peer's instrument. This manipulation will probably lead the second player to modify his or her play gestures in accordance to the new timbre that was received. These modified gestures can then be captured and transmitted to a third player, influencing this player's music playing in a reciprocal loop. Another example is a network that allows players to share musical motifs with other members of the group. By sending a motif to a co-player who can transform it and send it back to the group, participants can combine their musical ideas into a constantly evolving collaborative musical outcome.

The shape of the composition in such systems grows from the topology of the network and its interconnections with the performers. Such an environment that responds to input from individuals in a reciprocal loop can be likened to a musical "ecosystem." In this metaphor, the network serves as a habi-

Computer Music Journal, 29:2, pp. 23–39, Summer 2005

tat that supports its inhabitants (players) through a topology of interconnections and mutual responses that can, when successful, lead to new breeds of musical life forms. These interdependent connections can bring a wide range of new experiences into musical group playing. For example, a soloist can guide his or her collaborators with a simple interdependent touch toward a musical idea in which the soloist is interested, or change a supporting voice into a contrasting one so that a desired musical idea will become clearer. Players can shape their peers' accompaniment line so they would lead toward a new direction when the current one is exhausted, send a motif to other players who can manipulate it and send their variations back to the group, have a musical response accentuated by the player who sent the original call, plant a musical "seed" that would be picked up by the group in various manners, etc. Musical networks, therefore, bear the promise of using technology to enhance the social context of music performance and enrich its social ritual roots.

Technological and Historical Landmarks

The development of interconnected musical networks during the last half century is closely related to several technological developments that occurred during that time. In particular, I see four major innovations—analog electronics, the personal computer, the Internet, and alternate controllers—as principal enablers for the various approaches taken for interdependent musical connectivity. When these technologies became widespread and commercially available, they inspired musicians who were looking for new ways to expand the vocabulary of socio-musical expression.

Analog Electronics: The Early Musical Networks

John Cage was one of the first to notice the expressive potential that lies in using technology to enhance musical group interdependency by treating the then-recently invented commercial transistor radio as a musical instrument that could be used to provide a sonic medium for interdependent procedures, rules, and processes. Cage's compositions for transistor radios allowed, for the first time, for an external entity (audio steams from a set of radio stations) to generate and support evolving and dynamic musical contexts, providing a first crude glimpse at the concept of musical networks. Cage's 1951 *Imaginary Landscape No. 4* for twelve radio transistors played by 24 performers can be considered the first electronic interdependent musical network. The composition's score indicates the exact tuning and volume settings for each performer but with no foreknowledge of what might be broadcast at any specific time or whether a station even exists at any given dial setting. Inspired by the Chinese book of oracles, the *I Ching,* Cage demonstrated his fascination with chance operation, allowing players to control only partial aspects of the composition, while technology, chance, and performers together determined the actual audible content. The role of Cage as a composer was narrowed down to setting the high-level blueprint of dial-setting instructions.

The interdependency in the piece was manifested in two planes. First, there were the interdependent interactions between the players and the network of radio stations that provided unknown and dynamic musical content. But the system also supported intra-player interdependencies, as for every frequency-dial player there was a volume-dial player who could manipulate the final output gain, controlling a full continuum from complete muting to maximum amplification. The volume-dial players, therefore, had a significant impact on their peer's musical output, as they could control anything from rendering their actions inaudible, through blending them smoothly in the mix, to boosting them as a screaming solo.

The explorations of the transistor radio as an infrastructure for interdependency opened the door to further experimentation with interdependency. In *Cartridge Music* (1960), for example, Cage made his first attempt at a musical network focused on tactile generation of sounds and intra-player, amplification-based interdependencies. Here, players were instructed to pluck small objects (such as toothpicks or pins) that have been put into a gramophone cartridge and to hit larger objects (such as chairs) that were amplified with contact microphones. The simple, intra-player interdependency was generated owing to other players who controlled the amplifiers' volume knobs, leading, again, to a wide dynamic range of output from muting to soloing. On *Cartridge Music,* Cage remarked: "I had been concerned with composition which was indeterminate of its performance; but, in this instance, performance is made indeterminate of itself." Although revolutionary, the level of interdependency in Cage's early experiments were constrained by the crude nature of the technology, where, in effect, the only possible direct interpersonal connections were limited to coarse gain manipulations.

More elaborate attempts at analog interdependencies were made by composers such as Stockhausen, who in *Mikrophonie II* (1965), for example, routed the sound from four choruses and a Hammond organ to modulate each other's spectra through a single ring modulator, or David Tudor, who in *Rainforest IV* (1968) instructed players to attach microphones and contact loudspeakers to various objects on stage to create resonance-based feedback loops. The analog synthesizer provided an inspiring infrastructure for experimentalists such as David Rosenboom (1976) to use biofeedback methods for interconnecting groups of players to generate synthesized sounds, as well for popular music groups such Tangerine Dream to interdependently manipulate multiple synthesized sound parameters.

The Personal Computer: The Digital Advantage

The next significant breakthrough in technology for detailed and controllable interdependent networks was achieved thanks to the commercialization of the personal computer. One of the first commercial computers that was used for creating fine-tuned and configurable network topologies was the 1976 Commodore KIM-1. The League of Automatic Music Composers, a group of musicians from Oakland, California, that included John Bischoff, Jim Horton, and Rich Gold (later replaced by Tim Perkis) was one of the first to use a number of such KIM-1s to write interdependent computer compositions (see Figure 1.)

Each member in the group was able to send and receive data from and to his personal composition, which ran on his personal networked computer. The group named this new genre of music performance that allowed programmable and detailed musical interconnections "Network Computer Music." In their 1978 performance in Berkeley, California, for example, the group set up a three-node network, mapping frequencies from one computer to generate notes in another, or mapping intervals from one composition to control rests and rhythmic patterns in another. On this performance, the group wrote: "[W]hen the elements of the network are not connected, the music sounds like three completely independent processes, but when they are interconnected, the music seems to present a 'mindlike' aspect" (Bischoff, Gold, and Horton 1978). The League continued to work until 1986 when it evolved into an offspring group, The Hub, which employed more accurate communication schemes by using MIDI and central computers to facilitate the interaction. The Hub also experimented with more hierarchical systems, such as in *Waxlips* (1991), where a "lead player" sent cues to initiate new sections and to jump-start processes by "spraying" the network with requests for note messages. The Hub expanded their explorations to other areas such as remote collaboration and audience participation. In their first 1985 remote networking effort, the group was divided into two sites and communicated via telephone lines. Other pieces such as *HubRenga* (1989) attempted to involve the general public in on-line, remote, interdependent interactions. These early musical networks introduced the computer as a versatile and resourceful partner for interconnected group interaction. But the technology at that time could not yet support large-scale on-line interactions, nor was it designed to address novices with a wide range of musical backgrounds. Scot Gresham-Lancaster, a Hub member, reflects on the Hub's remote online experiments: "[T]he technology was so complex that we were unable to read a satisfactory point of expressivity" (Gresham-Lancaster 1998). Regarding the Hub's attempts to allow audience participation, he writes: "The varying range of taste and innate talent made for a pastiche that lacked fitness and cohesion, and despite the best intentions

Figure 1. An Early Musical Network: The League of Automatic Music Composers. Photo by Peter Abramowitsch.

of the contributors, the results were mixed." In the next two sections I present more recent approaches that were taken by musicians and researchers to use new technologies in an effort to allow for large-scale online musical networks as well as novice and audience participation.

The Internet: Approaches for Online Networks

Advanced Internet protocols and on-line applications today provide a faster and more reliable platform for large-scale interconnected musical networks. These developments helped facilitate the recent proliferation of on-line musical networks, offering a variety of musical activities for diverse audiences. Several recent studies attempt to classify and categorize online networks based on concepts such as location, media, timing, physicality, and other factors (see, for example, Barbosa 2003). Here, I attempt to map the field based on what I see as the central innovative concept of the medium: the level of interconnectivity among players and the role of the computer in enhancing the interdependent social relations. Based on these criteria, I have identified four different approaches and have named them the Server, the Bridge, the Shaper, and the Construction Kit.

The Server Approach

This simple approach uses the network merely as a means to send musical data to disconnected participants and does not take advantage of the opportunity to interconnect and communicate among players. Participants in such a client/server configuration cannot listen to or interact with their peers, and the musical activities are limited to the communication between each player and the central system. A typical example of the Server approach is the Sound Pool Web application, which is part of the interactive piece "Cathedral" by William Duckworth (Duckworth 1999). Here, a Beatnik-based Java applet allows individual players to trigger sounds by "accidentally or randomly" clicking on hidden nodes on the screen. The interaction occurs independently in each player's browser so that "each user can create his or her own unique experience." The original sounds in the piece were composed by Duckworth, but users can contribute their own sounds to the mix. Because there are no connections between participants, the system can support any number of users.

The Bridge Approach

The motivation behind the Bridge approach is to connect distanced players so that they can play and improvise as if they were in the same space. Unlike the Server approach, musical collaboration can occur in such networks because participants can listen and respond to each other while playing. However, the role of the network in this approach is not to enhance and enrich collaboration but to provide a technical solution for imitating traditional group collaboration. Aspects of bandwidth, simultaneity, synchronization, impact on host computer, and scalability are some of the challenges that are usually addressed in this approach. A characteristic example of the Bridge approach is the "Distribute Musical Rehearsal" project (Konstantas, et al. 1997), which focused on remote conducting. Using video streaming and a three-dimensional sound system, an ensemble of six players in Geneva was connected to a conductor in Bonn in an effort to rehearse *Dèrive* by Pierre Boulez. The system's goal was "giving the impression to the participants that they are physically in the same room," and the main challenges were minimizing transmission delay and accurately reproducing the sound space by using multiple microphones and a dummy head. The TransMIDI system (Gang, et al. 1997) addressed a similar challenge, but instead of sending audio, the system used the more efficient MIDI protocol that helped minimize latencies. By using the "Transis" group communication system, TransMIDI also allowed easy arrangement of multicast groups so that a "conductor" player could determine exactly what each participant heard at any time. Here, too, the system was aimed at bridging the distance between remote participants, allowing them to play, improvise, and listen to music in a way similar to a traditional "jam session."

The Shaper Approach

In the Shaper approach, the network's central system takes a more active musical role by algorithmically generating musical materials and allowing participants to collaboratively modify and shape these materials. Although players in Shaper networks can continuously listen and respond to the music that is modified by all participants, the approach does not support direct algorithmic interdependencies among players. One of the first attempts at this approach was the Palette (Yu 1996), which allowed on-line players to control aspects such as "style," "coherency," and "energy" of MIDI events that were generated based on input from other online players.

Another example of the Shaper approach can be demonstrated by the Pazellian application (Pazel, et al. 2000), a Web-based application that uses "Smart Harmony," an algorithmic mechanism that annotates each note with harmonic information and determines a set of harmonic constraints for the composition. Here, players could control parameters such as pitch range, volume, and instrumentation as well as manipulate multiple individual parameters for all voices in the composition. Players could hear and respond to the musical output that was generated by all the participants, but they could not directly communicate with any specific player. The "Variations for WWW" project (Yamagishi 1998) took a similar approach. In this system, a Max patch was connected to the Web via the W protocol so that remote users could manipulate parameters in an algorithmically generated theme. The Max patch sent MIDI commands to a MIDI synthesizer, which transmitted the audio output back to the participants via a Real Networks audio encoder. The system's interconnectivity was derived from its

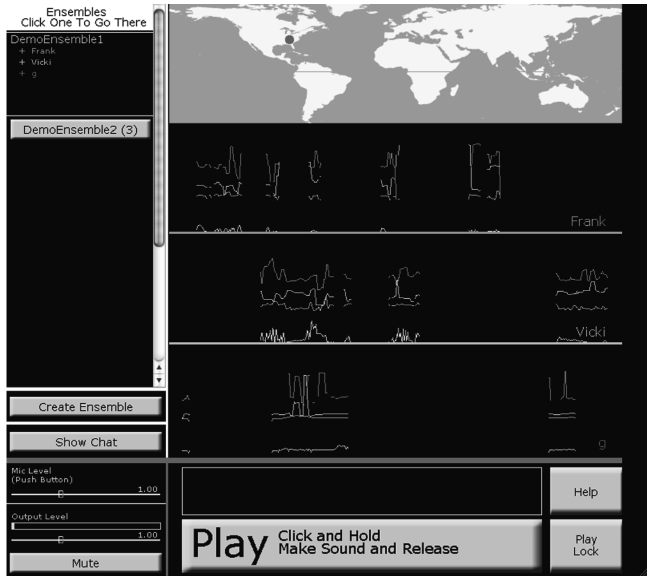


Figure 2. An online network: a screenshot from Auracle.

ability to play the combined manipulation of all users back to the participants, who could modify their musical contribution in response. A recent variation on this approach is the PIWeCS project (Whalley 2004) in which participants can shape and manipulate samples of Maori instruments using a multi-agent system. Here, too, the focus is not on generating original material but on modifying existing musical content.

The Construction Kit Approach

This approach offers higher levels of interconnectivity among participants, who are usually skilled musicians, by allowing them to contribute their music to multiple-user composition sessions, manipulate and shape their own and other players' music, and take part in a collective creation. Interaction in such networks is usually centralized and sequential as participants submit their pre-composed tracks to a central hub and manipulate their peers' material off-line. Faust Music On Line (Jordà 2002) is a representative example of this approach. Here, a Web-based synthesis engine allows players to create musical tracks and construct them into a composition that then can be downloaded by other participants. If the downloaded composition is not complete (i.e., it still has empty tracks) a participant can generate new tracks locally, add them to the composition, edit them, and upload the full piece back to the Web. Participants can also reprocess and distort any of the previous tracks in the composition by using a variety of synthesis generators and modifiers.

The WebDrum application (Burk 2000) demonstrates a slightly different take on the Construction Kit approach by basing the application on a traditional drum-pattern editor in which users turn notes on or off in a grid. Synthesized drum sounds are used to avoid downloading large audio sample files. Web users can play and listen to others participants' edits and add their instrument sounds to their own pallets.

Several projects attempt to combine the Construction Kit and the Shaper approaches. The ISX project (Helmuth 2000) allows users to algorithmically change their peers' sounds as well as to create new tracks from scratch and shape them into a collaborative composition. The project uses Internet2 as a wideband platform that can support the exchange of large audio files. The more recent Auracle system by Max Neuhaus (Freeman, et al. 2004, see www.auracle.org) analyzes vocal gestures from online players in real-time and uses these gestures to synthesize new sounds that can be heard by other users and added to in a synchronous multi-track format (see Figure 2).

Alternate Controllers: Gestures, Novices, and Real-Time Local Networks

Early musical networks tended to focus on complex interconnections among participants, often leading to "high-art" musical products that were not geared toward wide audiences. These networks posed high entrance barriers for players by requiring specialized musical skills and theoretical knowledge in order to take part in and follow the interaction in a meaningful manner. The problem of interaction coherency is accentuated in Internet-based musical networks that cannot support clear real-time gestural performance cues. It is clear that a graphical user interface cannot replace the personal, unmediated connection provided by tactile interaction with physical instruments in a local space. In an effort to facilitate expressive and more conveyable interconnected musical experiences, researchers are attempting to address novices and general audiences by simplifying and restricting the interaction and by using physical controllers, sensors, and gestural input in local spaces. I categorize these local networks into two groups: small-scale systems and large-scale systems. The two categories differ in the design challenges they impose and the approaches that designers are taking to address these challenges.

Small-Scale Local Systems

I define small-scale collaborative musical networks as those that support three to ten players in close proximity, which allows for detailed and subtle interpersonal interactions not possible with large-scale systems. Toshio Iwai's *Composition on the Table* (1998) is a representative example of an effective small-scale collaborative musical network for novices. The network is composed of four tables with various controllers such as switches, dials, and sliding boards that players can manipulate to control sound and projected images. In one of the applications, a grid is projected on the table, and players can direct animated objects by setting arrows at each node on the grid. When an object hits a node, a MIDI note is played so that interlocking loops and rhythms can be generated and controlled by the participants. The experience promotes collaboration when players follow each other's gestures and try to predict the object's movement, and therefore the music that will be generated.

Chris Brown's "Talking Drum," a local-area-network music installation (Brown 1999), is a collaborative system that attempts to address more skilled players by promoting thoughtful and intricate musical collaborations. Here, four computerized stations are installed in a large room or outdoors. Computer players (using MIDI instruments or computer mice) as well as acoustic instrument performers (playing to a microphone and an electronic pitch follower) interact with software that uses a genetic algorithm to create rhythmic units. The software responds to various aspects of users' playing (such as timing, loudness, density, and pitch) by changing parameters in the algorithms so that the rhythmic units are shaped by the players. The central system in this network (which runs on one of the four stations) coordinates timing and synchronization between stations.

Another approach for a gestural, collaborative music performance is taken by Sensorband (Bongers 1998), a group of three musicians that includes Edwin van der Heide, Zbiniew Karkowski, and Atau Tanaka. The group has built the "Soundnet," a giant web, measuring 11 × 11 meters, strung with thick shipping ropes. The trio performs on the instrument by climbing it as a set of stretch sensors at the end of the ropes measure the movements and send the data to control processing of recorded natural sounds. The instrument was purposely made too large for one person to master thoroughly, and the ropes "create a physical network of interdependent connections, so that no single sensor can be moved in a predictable way that is independent of the others." Some recent experimentations have also been made at a hybrid approach, which attempts to combine local and online networks. The reacTable (Jordà 2003), for example, is table-based multi-user instrument that can be played collaboratively both off- and online at the same time.

A set of local musical networks was developed by the author as part of his research into music interdependency. The Musical Fireflies (Weinberg, Lackner, and Jay 2000) are wireless rhythmic instruments that can be synchronized when an infrared link is established between them. Players can record rhythmic patterns and trade timbres and rhythms with each other. The collaborative interaction introduces players hands-on to complex musical concepts such as polyrhythm. The "Squeezables" instrument (Weinberg and Gan 2001) presents a different approach for a local, interdependent musical interaction. The instrument, composed of six squeezable and retractable gel balls mounted on a small podium, allows a group of players to perform and improvise musical compositions using a set of squeezing and pulling gestures. The activity level of the "accompaniment balls" is measured and mapped to influence the melody ball's pitch and timbre. The melody player can control the accompaniment players' level of

Figure 3. Using the Beatbug handheld controller, players create, share, and interdependently modify rhythmic patterns in a group.

Figure 4. Voice Networks-participants record and interdependently transform their voices to create collaborative vocal compositions.

influence through his or her own squeezing and pulling gestures. The Beatbugs network (Weinberg, Aimi, and Jennings 2002) features more advanced collaborative rhythmic interaction. Here, players use instruments called Beatbugs to enter rhythmic motifs that can be sent and shared by their peers. Receiving players can develop the motifs in real time by ornamenting the rhythm and the melodic contour through the manipulation of two bend-sensor antennae, which leads to the creation of a constantly evolving, multi-player, collaborative musical composition (see Figure 3). A more recent local network installation is "Voice Network" (Weinberg 2004). Here, players can record, transform, and share their voices in a group. A central computer system facilitates the interaction as participants interdependently collaborate in developing their vocal motifs into a coherent musical composition (see Figure 4).

Large-Scale Local Systems

I define large-scale musical networks as systems that are designed for more than ten participants. Here, the details and subtleties of individual contributions are often hidden by the large quantities of participants. The central system, therefore, often focuses on analyzing the large-scale group interaction patterns and coordinating the multiple input sources into a meaningful musical outcome. One of the earliest attempts at creating a large-scale collaborative musical system for novices was Tod Machover's *Brain Opera* (see brainop.media.mit.edu). In this project, audience members were able to experiment with a number of new instruments such as the "Rhythm Tree," which included dozens of drum pads wired to trigger percussive sounds and word fragments; the "Gesture Wall," where visitors' body movements were captured to control the musical output; and the "Singing Tree," which manipulated MIDI-based accompaniment in correlation to the "pureness" of participants' singing. The physical and intuitive operation of these instruments allowed almost any visitor, from children to senior citizens, to take part in an expressive interaction with the electronic sound. The *Brain Opera* instruments, however, were not designed to communicate with each other, and it was left for the players to coordinate their actions if so desired.

An example of a computer-coordinated, large-scale local musical network is found in Feldmeier, Malinowski, and Paradiso (2002). Here, players use a set of low-cost, wireless motion sensors that allow for a large group of participants (up to hundreds) to control and influence the music that they are dancing to. The system does not identify each performer but measures and reacts to the characteristics of the group in general. Algorithms based on temporal and frequency analysis of the data are used for detecting group behavior and mapping it to the generated musical material. Aspects such as tempo, layers, rhythmic complexity, timbre, and register are controlled and manipulated in correlation to the level of activity of the group. Results show that groups are more active and synchronized when controlling the music as opposed to a non-interactive control group.

A different, more centralized approach for a large-scale musical network is Golan Levin's *Dialtones: Telesymphony* (2001; see www.flong.com/telesymphony). Here, the musical material was pre-composed and generated by orchestrating the dialing and ringing of audience members's mobile phones. The composer downloaded ring tones into participants' cell phones, registered their numbers, and set the participants in a grid of 10 × 20 members. During the concert, performers called each other's cell phones in an orchestrated manner, and players were asked to raise their cell phones when being called to help represent the interaction and the music to viewers and other participants. A projected grid helped audience and performers follow the activity, which led to a coherent musical outcome. But to support this coherency, players in *Dialtones* were stripped of any meaningful musical contribution and were essentially used as a grid of speakers for the composer's musical ideas. In this sense, the work demonstrates the difficulty in creating a coherent musical outcome while still allowing a large group of players to meaningfully participate in the musical activity.

Toward a Theoretical Framework of Musical Interconnectivity

Informed by the historical review and the classification framework proposed above, I here attempt to identify the theoretical and practical principles that are at the core of musical interconnectivity. I believe that the taxonomy that I propose may also be useful for musical network designers in thinking and communicating their ideas about the field. My investigation is based on a number of anchoring questions, including "Why?" (what are the goals and motivations for designing and participating in a musical network?), "How?" (what are the different social perspectives, architectures, and network topologies that can be used to address these goals and motivations?), and "What?" (what are the musical parameters and interdependent algorithms that can be used in the network, filling the architectural form with musical content?). As part of this analysis, I will address the advantages and disadvantages of a variety of approaches taken by musicians and designers and will suggest a scheme for maintaining a well-balanced system that maximizes the benefits.

Goals and Motivations

The definition of "Interconnected Musical Networks" as live performance systems that allow players to influence, share, and shape each other's music in real-time (Weinberg 2002) suggests that the network should be interdependent, dynamic, and function as a facilitator of social interactions. An investigation of the rationale behind designing and participating in such musical networks leads to a further classification of these motivations into two major network categories: process-centered networks and structure-centered networks. This differentiation can be related to the tension that emerged in the midst of the 20th century between the radicalization of musical structure and composer control, practiced mainly by "avant-garde" and "post-serialist" composers such as Karlheinz Stockhausen and Pierre Boulez on one hand, and the escape from structure toward "process music" as was explored mostly by American experimentalists such as John Cage and Steve Reich. As opposed to the European movements that emphasized composer control over almost every aspect of the composition, process music came from the belief that music can be a procedural and emergent art form and that there are many ways of handling form other than constructing structures in different sizes. In such procedural process-based music, the composer sacrifices certain aspects of direct control to create an evolving context by allowing rules (in closed systems) and performers (in open ones) to determine and shape the nature of music. John Cage addressed this tension referring to his own experience: "I was to move from structure to process, from music as an object having parts to music without beginning, middle or end, music as weather" (Cage 1961).

Figure 5: Motivations for a process-centered musical network.

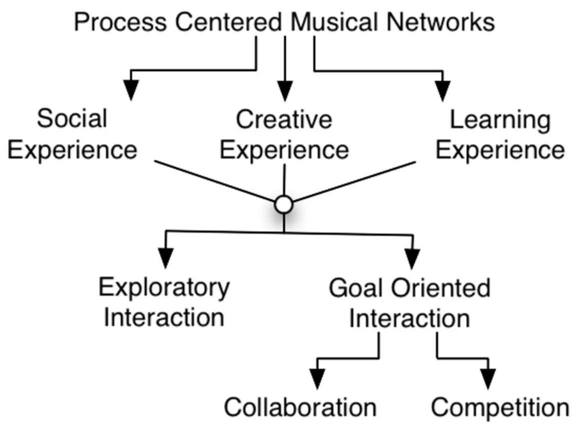
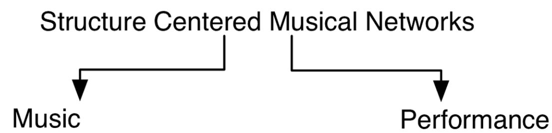


Figure 6: Motivations for structure-centered musical network.



The use of technology in musical networks pushes the tension between structure and process music further into an experience where predetermined rules and instructions, combined with improvised interdependent group interactions, lead to evolving musical behaviors, giving a new meaning to Cage's exploration of unpredictability, chance determination processes, accidents, and contextual music. In my analysis, I will accentuate the differences between these categories for argumentative clarity. It should be noted, though, that most investigated networks combine process and structural elements in different levels and balances.

The focus in process-centered networks, as can be seen in most of the local networks for novices described above, is on the player's experience, whether it is social, creative, or educational (see Figure 5). For designers of such networks, the musical outcome of the interaction is usually less important than the process participants undertake while creating this outcome. Some process-oriented networks, such as the Beatbug network, focus on facilitating elaborate social dynamics between players; others, such as Composition on a Table, emphasize the expressive and creative process for individual players; and still others, such as the Musical Fireflies, center on providing a learning experience. The interaction in process-centered systems can be further classified into two additional subcategories: exploratory and goal-oriented interactions. Exploratory networks do not impose specific directions or goals for the participants. These systems are driven by motivations such as the investigation of novel ways for playing in a group or the creation of unexplored musical crossbred offspring (as with the League of Automatic Music Composers). Goal-oriented interactions, on the other hand (such as in the Feldmeier's synchronized dancing network), are designed to encourage players to achieve specific objectives, musical or non-musical. Such activities can be designed to reward participants for their social skills, musical creativity, or learning achievements and can offer tasks that are based on encouraging collaboration or competition.

In structure-based systems, on the other hand, the main goal of the interaction tends to focus on its outcome, whether it is the music or the performance (see Figure 6). For designers of structure-centered systems, the player's experience is relevant only in regard to this final outcome. Most of the early networks, which stem from the "high-art" music world, fall under this category. Composers and designers of such systems are usually more interested in aspects such as artistic vision, compositional arrangement, and performance. Players in such networks, on the other hand, are expected to realize the artistic vision of the composer. It is important to note that although most networks combine process and structure-based elements, creating a successful balance between these aspects is not a trivial task, as many of the elements are contradictory in nature. For example, it would be a difficult task to design a musical network that would lead to the creation of an interesting, well-structured composition while players are trying to win a musical game.

Social Organization and Perspectives

Similarly to other social systems, musical networks are based on social organizations, which can be informed by "social philosophies." The main conceptual axes at play when designing a "social

Figure 7. Centralized social perspectives.

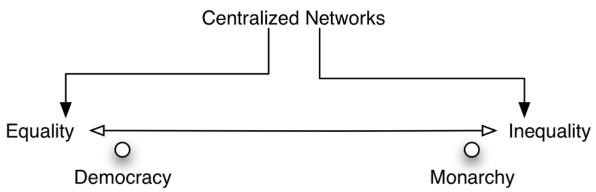
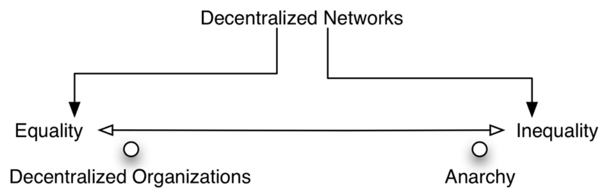


Figure 8. Decentralized social perspectives.



philosophy" for a network are the level of central control desired and the level of equality provided to the different participants in the interaction. Centralized systems, such as in the case of online networks from the "Shaper" variety, tend to be governed by a computerized hub that is responsible for generating the musical output based on input from participants. In decentralized systems such as the Musical Fireflies, players communicate directly with each other through instruments or software applications that are computationally self-contained. Under the centralized and decentralized umbrellas, we can find a wide range of approaches that are based on the levels of equality provided to participants in terms of their musical role (see Figures 7 and 8). Political metaphors may be appropriate. For example, a "monarchic" system, such as in Golan Levin's *Telesymphony,* demonstrates a centralized unequal social approach. Here, a leader—a human or in some cases the computer—controls and conducts the interaction. This leader can provide temporary freedom to other players when desired, change and manipulates the interconnection gates among players, and take control over the interaction in general.

Although providing a composed and structured interdependent outcome, the monarchy approach usually fails in providing a true collaborative and creative voice to players owing to the leader's dominance. Such systems, therefore, would be more effective in addressing structure-centered motivations than process-centered ones. Democratic networks, on the other hand (such as in the Squeezables network), can be more effective when process is emphasized. Here, the centralized system provides an equal, or almost equal, role for each player in defining the musical output. In goal-oriented democratic systems, participants would have to collaborate to create a noticeable and significant musical effect. Often in such systems, only the collaborative act of the majority defines the final musical result. Different participants in democratic networks might have different roles and responsibilities (such as controlling the harmony, melody, or rhythm), while individual players might temporarily receive a leading role from their peers or from the system.

In decentralized systems, on the other hand, interaction occurs directly between participants without a central control to govern the experience. One extreme example of a decentralized unequal musical network is an "anarchic" network, which provides minimum central control and maximum freedom for players to generate and manipulate their musical material, such as in Tod Machover's *Brain Opera.* An interesting hybrid approach is the concept of Network Computer Music by The League of Automatic Music Composers, which experimented with synchronous decentralized but democracy-oriented networks. Another unique decentralized approach is a rule-based network where high-level musical patterns emerge from the interaction between a large number of participants who follow identical simple rules (see Resnick 1999).

Architectures and Topologies

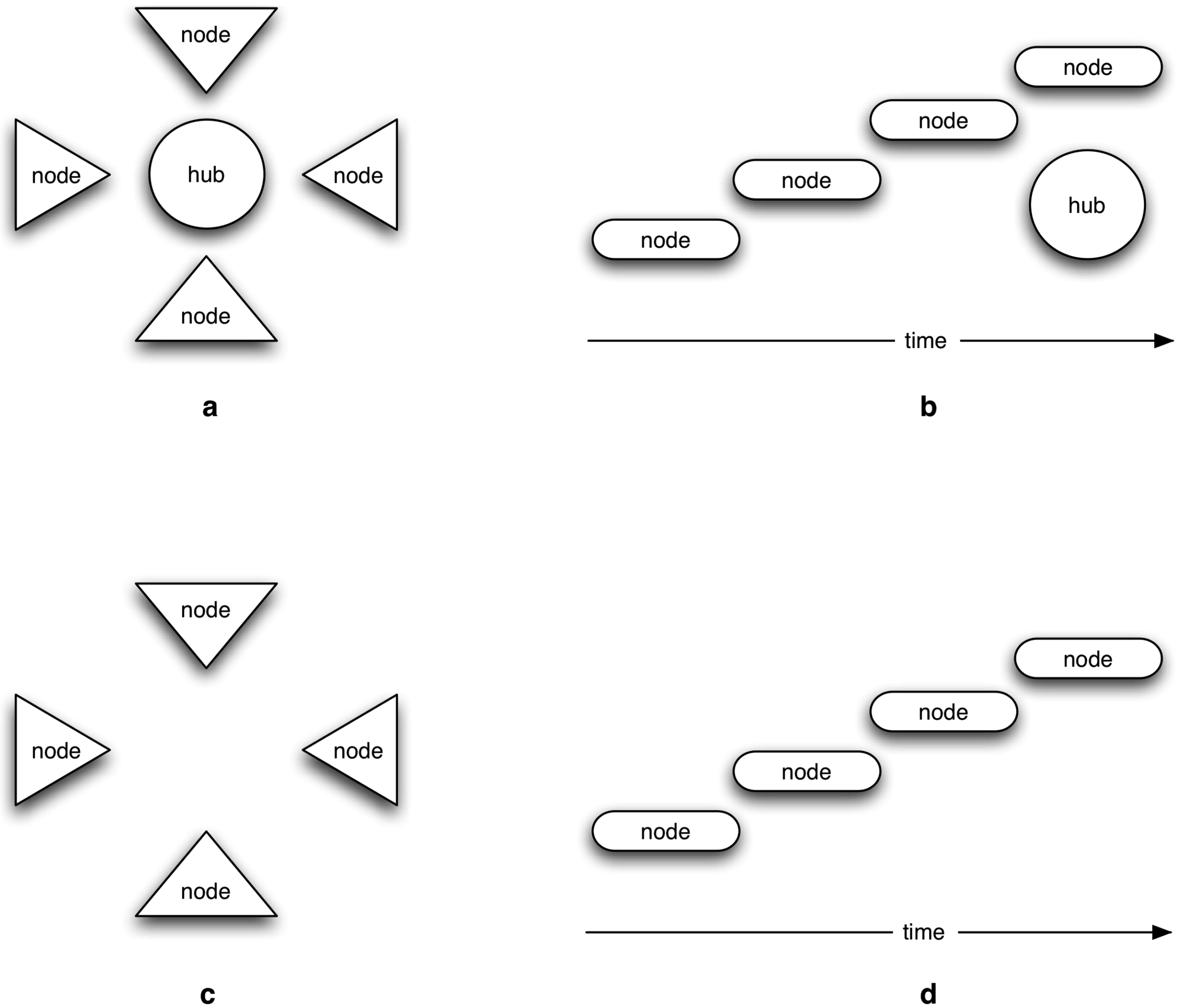
The social organization of the network, an abstract, high-level notion, is addressed by designing and implementing the lower-level aspects of the network's topology and architecture. Here too, the categorization into centralized and decentralized networks is pivotal. In this classification, centralized networks allow players to interact through instruments and controllers that do not have direct influence on each other. Data from players are sent to a computerized hub for analysis and algorithmic generation of the musical output (as in the case of most of the online networks, the Squeezables, *Telesymphony,* and others). In decentralized topologies, on the other hand, players interact directly with each other using in-

Figure 9a. Synchronous centralized network: "flower" topology.

Figure 9b. Synchronous centralized network: "wheelbarrow" topology.

Figure 9c. Synchronous decentralized interaction: "star" topology.

Figure 9d. Sequential decentralized interaction: "stairs" topology.



struments or applications that have their own computational function (such as with Cage's *Imaginary Landscape 4*, the League of Automatic Music Composers, the Musical Fireflies, and others).

Centralized and decentralized topologies can be classified into two additional subcategories: synchronous (or real-time) and sequential (or non-real-time). In synchronous networks, players modify and manipulate the music of their peers while it is being played. In sequential systems, players generate their musical material with no outside influence and only then "submit" it to further transformation and development by their peers. At its simplest form, a centralized synchronous network can be depicted as having a "flower" topology (see Figure 9a). The different input nodes in the network, which represent the players, are constantly connected to a computer hub that is responsible for creating the interconnections among the nodes. A centralized sequential network can be depicted as having a "wheelbarrow" topology (see Figure 9b). Here the inputs nodes, or players, are separated from each other in the time domain, as each new input stage builds upon the last one.

Figures 9c and 9d depict the decentralized versions

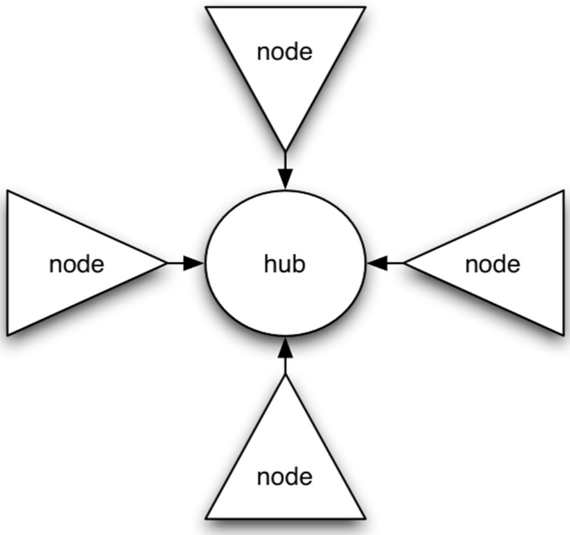


Figure 10. Symmetric, one-way "flower."

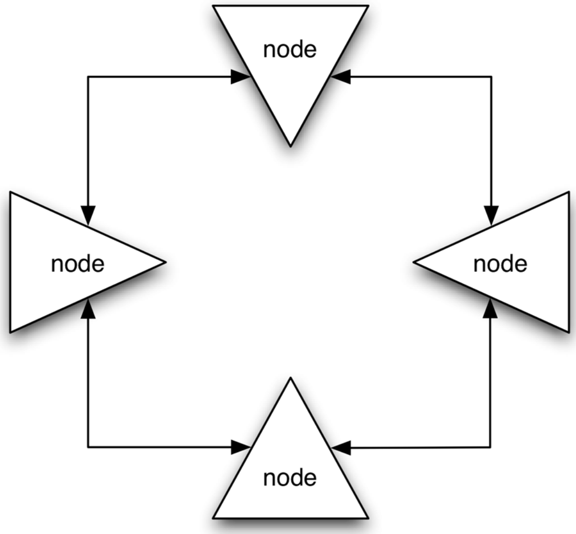


Figure 11. Symmetric, interdependent "star."

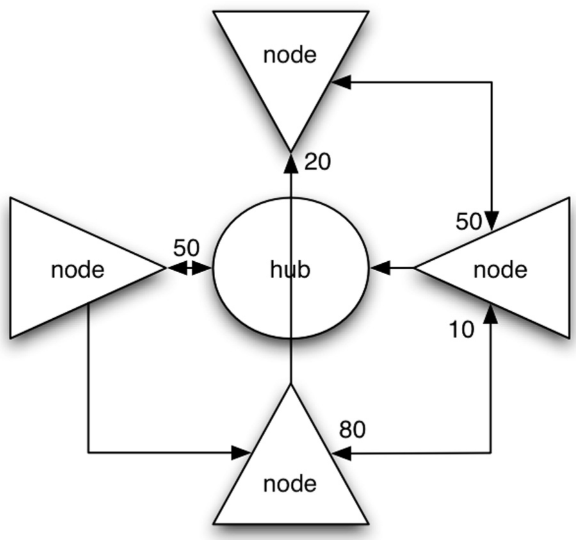


Figure 12. Asymmetric, weighted interdependent "flower."

of the flower and wheelbarrow topologies and can be titled as "star" and "stairs" topologies, respectively. Synchronous interactions are more likely to be supported by local-area networks in which latency is less of a problem in comparison to remote networks. Synchronous networks are also more likely to support constantly evolving and immersive musical experiences, although such an approach can also lead individual players to lose the sense of coherency and causality if the network topology is not designed carefully to maintain aspects of individual autonomy. In sequential systems, on the other hand, the interdependent interactions occur in an ordered manner by turn-taking procedures. This approach is more tolerant to latency, can be easily supported by remote online networks, and is usually simpler to follow for the individual player. However, in sequential networks, the real-time group experience might involve compromise, because all players are not always involved in music-making.

These generic depictions of synchronous, sequential, centralized, and decentralized interactions do not represent the directionality and the nature of the connections among the nodes in the network. A more detailed depiction can be seen in Figures 10–17. Figure 10 depicts simple one-way flower architecture. Here, data is sent synchronously from the players to the hub, which is responsible for generating the musical output based on algorithmic treatment of musical and gestural input. The interdependent aspects in this simple network are derived only from the players, who listen to the musical output from the hub and change their actions accordingly, as can be seen in the Pazelian application (Pazel, et al. 2000), for example. A higher level of interdependency is depicted in Figure 11, which shows a decentralized star topology where players are connected

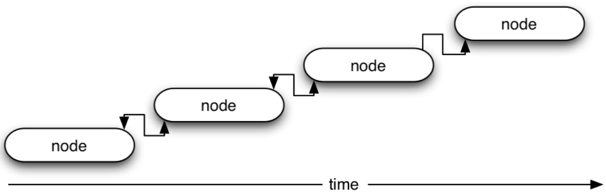


Figure 13. Symmetric, one-level "stairs."

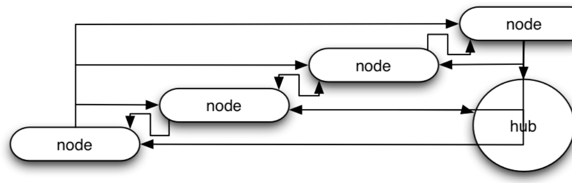


Figure 14. Symmetric, multi-level "wheelbarrow."

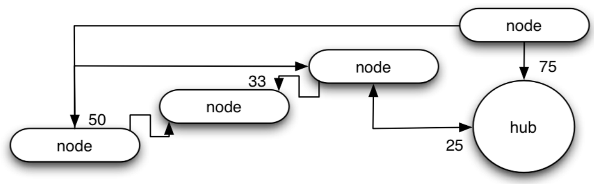


Figure 15. Asymmetric, multi-level, weighted "wheelbarrow."

directly to each other and can interdependently manipulate each other's musical output such as in the case of the FMOL project. Cage's *Imaginary Landscape No. 4,* on the other hand, can be seen as a synchrotrons anarchic decentralized network with a symmetric interconnection scheme.

Both Figures 10 and 11 depict symmetric topologies, where all nodes are connected to the hub or to each other. Such architectures would be best suited to support an "equal" social approach. Figure 12, on the other hand, presents an asymmetric (unequal) network architecture where connections are possible only in specific directions and in between specific nodes. Figure 12 also introduces the concept of *weighted gates* that control the level of influence at each intersection in the network. Normally, gates would be open, providing a full level of influence, whether for algorithmic control or musical content. The gates, however, can also be partly (or fully) shut, allowing only a limited level of functionality at each particular intersection. Gates can have different weights as default values (depicted as numbers next to some intersections in Figure 12) but can also be changed and manipulated in real time based on a player's input, such as in the Squeezables network. This asymmetric weighted flower topology is common in democratic networks, as it provides different roles and levels of importance to the different players. An extreme version of this approach can lead to a monarchic network where one player can control all the weighted gates in the system and therefore gain full power in conducting the interaction, such as in Golan Levin's *Telesymphony.*

Sequential networks have similar kinds of interconnected topologies. In the simplest architecture, each node is only connected to the next one so that every player can manipulate the musical product of the previous player, such as in the case of the Musical Fireflies. Figure 13 depicts such a symmetric, one-level stairs topology. The arrows between steps are bidirectional; the outgoing arrows represent the musical output that is sent to the next node, and the incoming arrows represent the algorithmic manipulation that is applied to it. More elaborate sequential topologies allow players to transform not only the previous player's musical output but also the musical product of the other participants in different nodes of the network and at different times. These transformations can be applied directly among players or through a central hub. Such a symmetric multi-level wheelbarrow topology is depicted in Figure 14. Similarly to synchronous networks, asymmetric sequential networks can facilitate interdependent interaction only in specific directions and provide idiosyncratic roles to the different players. Here too, weighted gates can be assigned to the intersections (see Figure 15).

In practice, most elaborate musical networks combine synchronous and sequential elements in different balances. In such hybrid networks (such as the Beatbug network), part of the interaction is sequential (as players have autonomous control over their own music before sharing it with the group), while other parts of the interaction are synchronous, when players can influence their peers's musical output in real-time. In addition, certain sections of the interaction can be centralized, and others can be decentralized. In general, these hybrid systems can be

Figure 16. Hybrid, generic "Stairs of Flowers."

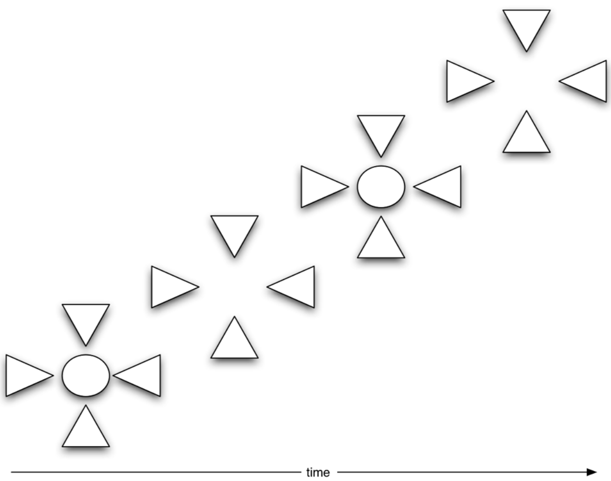
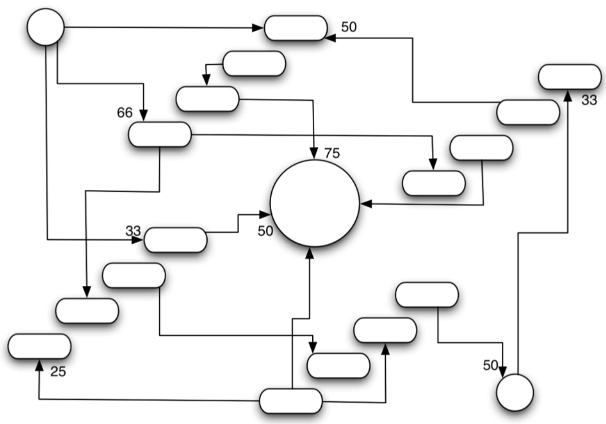


Figure 17. Hybrid, interconnected "Flower of Stairs" with weighted gates.



depicted in two manners: "Stairs of Flowers," where synchronous interactions are ordered sequentially in time (see Figure 16), and "Flowers of Stairs," where a set of sequential interactions are synchronously connected to the system's hub (see Figure 17). A weight system can also be assigned and controlled in real time to provide dynamic levels of influence.

Musical Content and Control

Making decisions about the motivations, social perspectives, and the network architectures are essential steps towards setting the framework for an effective musical network project. But of great importance for the final musical result are the lower-level decisions regarding the actual musical parameters and transformation algorithms that would infuse such a framework with musical content. Of unique importance are decisions regarding the musical parameters and functions that would be generated and controlled autonomously as opposed to those that would be controlled interdependently. This aspect of the design bears a subjective aesthetic core, as different composers and designers would have different ideas, tastes, or artistic interests when determining the precise control parameters. The musical content and transformation decisions are informed by the higher-level design decisions. For example, an exploratory, anarchic flower topology would be best served by allowing players to generate and manipulate a full gamut of pitches, timbres, timing, and expression aspects and by applying constantly changing random transformation algorithms. On the other extreme, a system that would limit the possibilities for input and manipulation by allowing players to choose from a limited bank of presets in an effort to achieve a specific task is likely to support a goal-oriented sequential structured topology.

Generally speaking, every musical parameter, such as pitch, rhythm, timbre, or dynamics, is a candidate for autonomous as well as interdependent control. However, there are some rules of thumb that have been proven to be effective for the creation of a coherent yet collaborative and immersive interaction. For example, allowing players to influence and control parameters such as pitch or contour of a peer's melody may lead to an incoherent experience for the peer who may loose control over some of the fundamental aspects of the melodic production. Such mappings may draw the systems into an anarchic experience that is difficult to follow for participants and viewers, even if the architecture supports other social perspectives. On the other hand, granting a player full autonomous control over his or her pitch content while allowing other players to control ornamental and expressive aspects such as timbre or dynamics tend to lead to more coherent experience for the melody player. Here, the melody player can interdependently enrich his or her own playing experience while attempting to accommodate the melody to the new timbres and dynamics.

Another important aspect for maintaining the interaction coherency is preserving the nature of the musical material as it was originally created. In sequential networks in particular, it is easy to allow co-players to modify their peers's music beyond recognition. This might disconnect the original players from the music they created, obscuring their detailed idiosyncratic contribution to the group. The interdependent transformation algorithms, therefore, can be more effective if they attempt to modify surface elements and to maintain reversibility, so that the original musical output would be perceivable and retrievable.

A Final Note

The field of interconnected musical networks has matured and is currently expanding to new audiences and new platforms such as wireless communication devices (see, for example, McAllister et al. 2004; Tanaka et al. 2004). If the field is to continue to grow, then composers, performers, and audiences will require a solid theoretical framework of reference when composing, designing, participating in, or listening to interconnected musical networks. In this article, I attempted to define the fundamental aspects for such a theoretical framework by mapping the field, addressing aesthetics and technical concepts and motivations, and providing design suggestions based on an investigation and analysis of historic and current work. I plan to modify and expand this theoretical framework in correlation to the constantly evolving changes in technology and artistic focus in the field.

Acknowledgments

I would like to thank the Hyperinstrument Group at MIT Media Lab and Tod Machover for his support and advice.

References

Barbosa, A. 2003. "Displaced Soundscapes: A Survey of Network Systems for Music and Sonic Art Creation." *Leonardo Music Journal* 13:53–59.

Benzon, W. L. 2001. *Beethoven's Anvil: Music in Mind and Culture.* New York: Basic Books.

Bischoff, J., R. Gold, and J. Horton. 1978. "Microcomputer Network Music." *Computer Music Journal* 2(3):24–29.

Bongers, B. 1998. "An Interview with Sensorband." *Computer Music Journal* 22(1):13–24.

Brown, C. 1999. "Talking Drum: A Local Area Network Music Installation." *Leonardo Music Journal* 9:23–28.

Burk, P. L. 2000. "Jammin' on the Web—A New Client/Server Architecture for Multi-User Performance." *Proceedings of the 2000 International Computer Music Conference.* San Francisco, California: International Computer Music Association, pp. 117–120.

Cage, J. 1961. *Silence.* Middletown, Connecticut: Wesleyan University Press.

Duckworth, W. 1999. "Making Music on the Web." *Leonardo Music Journal* 9:13–18.

Feldmeier, M., M. Malinowski, and J. Paradiso. 2002. "Large Group Musical Interaction Using Disposable Wireless Motion Sensors." *Proceedings of the 2002 International Computer Music Conference.* San Francisco, California: International Computer Music Association, pp. 83–87.

Freeman, J., et al. 2004. "Adaptive High-level Classification of Vocal Gestures Within a Networked Sound Instrument." *Proceedings of the 2004 International Computer Music Conference.* San Francisco, California: International Computer Music Association, pp. 668–671.

Gang, D., et al. 1997. "TRANSmidi: A System For midi Sessions Over the Network Using Transis." *Proceedings of the 1997 International Computer Music Conference.* San Francisco, California: International Computer Music Association, pp. 283–286.

Gresham-Lancaster, S. 1998. "The Aesthetics and History of the Hub: The Effects of Changing Technology on Network Computer Music." *Leonardo Music Journal* 8:39–44.

Helmuth, M. 2000. "Sound Exchange and Performance on Internet2." *Proceedings of the 2000 International Computer Music Conference.* San Francisco, California: International Computer Music Association, pp. 121–124.

Hinton, M., and D. Morgenstern. 1988. *Bass Line: The Stories and Photographs of Milt Hinton.* Philadelphia, Pennsylvania: Temple University Press.

Iwai, T. 1998. *Composition on the Table.* Exhibition at Millennium Dome 2000, London.
Jordà S. 2002. "FMOL: Toward User-Friendly, Sophisticated New Musical Instruments." *Computer Music Journal* 26(1):40–50.
Jordà, S. 2003. "Sonigraphical Instruments: From FMOL to the reacTable." *Proceedings of the 2003 Conference on New Interfaces for Musical Expression,* Montreal, pp. 121–124.
Konstantas, D., et al. 1997. "Distributed Musical Rehearsal." *Proceedings of the 1997 International Computer Music Conference.* San Francisco, California: International Computer Music Association, pp. 279–282.
Levin, G. (2001) *Dialtone: A Telesymphony.* Premier at Ars Electronica Linz Austria. Available at www.flong.com/telesymphony/.
McAllister, G., M. Alcorn, and P. Strain. 2004. "Interactive Performance With Wireless PDA." *Proceedings of the 2004 International Computer Music Conference.* San Francisco, California: International Computer Music Association, pp. 702–705.
Pazel, D., et al. 2000. "A Distributed Interactive Music Application Using Harmonic Constraint." *Proceedings of the 2000 International Computer Music Conference.* Berlin: International Computer Music Association, pp. 113–116.
Rasch, R. A. 1988. "Timing and Synchronization in Ensemble Performance." In J. Sloboda, ed. *Generative Processes in Music.* Oxford: Clarendon Press, pp. 70–90.
Resnick, M. 1999. *Turtles, Termites and Traffic Jams: Explorations in Massively Parallel Microworlds.* Cambridge, Massachusetts: MIT Press.
Rosenboom, D., ed. 1976. *Biofeedback and the Arts: Results of Early Experiments.* Vancouver: Aesthetics Research Centre of Canada.
Tanaka, A., et al. 2004. "Enhancing Musical Experience Through Proximal Interaction." *Proceedings of the 2004 International Computer Music Conference.* San Francisco: International Computer Music Association, pp. 205–208.
Weinberg, G. 2002. "The Aesthetics, History, and Future Challenges of Interconnected Music Networks." *Proceedings of the 2002 International Computer Music Conference.* San Francisco: International Computer Music Association, pp. 349–358.
Weinberg, G. 2004. "Voice Networks: Exploring the Human Voice as a Creative Medium for Musical Collaboration." *Proceedings of the 2004 International Computer Music Conference.* San Francisco, California: International Computer Music Association, pp. 623–626.
Weinberg, G., R. Aimi, and K. Jennings. 2002. "The Beatbug Network: A Rhythmic System for Interdependent Group Collaboration." *Proceedings of the 2002 Conference on New Interfaces for Musical Expression.* Dublin, pp. 107–111.
Weinberg, G., and S. Gan. 2001. "The Squeezables: Toward an Expressive and Interdependent Multi-player Musical Instrument." *Computer Music Journal* 25(2):37–45.
Weinberg, G., T. Lackner, and J. Jay. 2000. "The Musical Fireflies: Learning About Mathematical Patterns in Music Through Expression and Play." *Proceedings of the 2000 Colloquium on Musical Informatics.* L'Aquila, Italy: Instituto GRAMMA, pp. 146–149.
Whalley, I. 2004. "Adding Machine Cognition to Web-Based Interactive Composition." *Proceedings of the 2004 International Computer Music Conference.* San Francisco, California: International Computer Music Association, pp. 196–200.
Yamagishi, S. 1998. "Variations for WWW." *Proceedings of the 1998 International Computer Music Conference.* San Francisco: International Computer Music Association, pp. 510–513.
Yu, J. 1996. "Computer Generated Music Composition." Master's Thesis, MIT.