ACTUATED ACOUSTIC INSTRUMENTS: RELATIONSHIPS AND MIND-SETS

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Abstract

Researchers in the burgeoning field of actuated acoustic instruments seek to endow musical instruments with new capabilities through the use of electromagnetic and electromechanical technologies. These added technologies inevitably alter the relationships of performers, composers and audiences to the affected instruments. This document explores those various relationships and some of the effects changes to those relationships have.

The first chapter examines unaltered acoustic musical instruments through the lens of Human-Computer Interaction (HCI) to establish a framework for looking at musical instruments generally. Instruments are considered as interfaces for music making, with inputs and outputs that engage performers in various ways. Audiences’ relationships with instruments are considered here as well, particularly in terms of how the audience’s understanding of the performer/instrument relationship contributes to an embodied musical understanding.

With that framework in place, Chapter 2 looks at specific musical works in which an intervening mechanism or technology alters an instrument’s behavior in some way. The piano serves as a case study of these issues with canonical works by Cowell and Cage illustrating two distinct ways the performer/instrument relationship may be altered. The chapter also examines two actuated piano systems, works written for them, and how design choices give insight into how the systems’ designers and composers imagine their systems being used.
The third chapter begins with a brief discussion of actuated acoustic instruments generally. Following is an in-depth examination of an electromagnetically actuated vibraphone, the EMvibe. Technical aspects of the EMvibe are discussed with special attention paid to the ways in which technical decisions are informed by the acoustic and mechanical properties of the vibraphone. Questions about interfacing are considered as well: How are the new capabilities accessed? How might those capabilities be used musically? How do the interface choices affect musical possibilities and vice versa?

Finally, taking a 30,000-foot view of the field, the concluding chapter considers why composers and instrument designers might be interested in altering instruments at all. What do they gain by deliberately disrupting or upsetting their relationship to a previously familiar instrument?

The compositions “Fill Up Jar” and “Ctenophora” complete this dissertation.
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To my parents
1 The Instrument/Interface

1.1 The NiloiV

The NiloiV is an interface for musical expression that provides continuous control over the frequency, amplitude and timbre of four oscillators. The frequency of each oscillator is controlled by the left hand via a dedicated linear position sensor and the amplitude is controlled by means of wireless input wand held in the right hand.

The flexible linear position sensors are suspended above a rigid substrate. Position is determined by the location at which the sensor contacts the substrate when pressed. The linear position sensors provide continuous frequency control over roughly two octaves with position mapped logarithmically to frequency. The wand is both pressure and velocity sensitive affording the user extremely fine-grained control over the oscillator’s amplitude envelope. The oscillators are sustained by drawing the wand perpendicular to the linear position sensors. By plucking the linear position sensor directly, the user is able to generate sharp attack envelopes with rather quick decays, though in this mode the user sacrifices continuous control over the amplitude. The position of the wand along the length of the linear position sensor affords the user control over the spectral content of the oscillator, providing yet another control axis. The pressure of the wand on the linear position sensor also affects the spectral shape of the output. The interface has an integrated acoustic resonator that is held between the user’s chin and left shoulder in performance. Additional support is provided by the left hand leaving the right hand free to manipulate the wand.
Feedback is provided to the user through several channels. Auditory feedback is provided with zero latency through the integrated acoustic resonator, and, owing to the interface’s idiosyncratic performance technique, through bone conduction via the user’s jaw. The linear position sensors track absolute location, thus the user may draw visual cues from the position along the sensor. The vertical distance between the sensor and substrate provide the user with tactile feedback. In addition, sensors are mechanically coupled to the oscillator providing the user with haptic feedback as well.

The violin is an incredible interface for making music. When described similarly—in terms of its inputs and outputs—virtually any acoustic musical instrument can be viewed as a multi-modal interface of extremely high resolution. Even more astonishing than the sensitivity of musical instruments themselves is the fact that humans are able to leverage that sensitivity to do extraordinary things with them. Through their instruments, performers predictably execute complicated motor activities, instantaneously perceiving incoming information and making adjustments based on that information.

Our experience as humans living in a physical world enable us to perform high-order physical tasks without being conscious of the constituent motor tasks that go into them. We can drink coffee (usually) without spilling, ride a bicycle, or chew gum and walk at the same time. These activities seem incredible if we pause to think about them because we can’t really think about how we do them. Of course these skills have to be practiced and learned, but once learned, that knowledge doesn’t ultimately reside in our brains in a way our conscious minds can access.
As with other skills, much of the knowledge of expert performers exists in the body, the result of countless hours of practice and years of training. Like other “action-centered skills,” much of the knowledge necessary for musical performance is accumulated by our kinesthetic sense. Once acquired, this type of knowledge is not available for analysis or contemplation; it is tacit knowledge.¹

Given the essential role they play in the production of music, one might expect the subject of instruments to arise more often than turns out to be the case. That expert skill is a form of tacit intelligence at least partially explains the lack of first-hand accounts of how musicians relate to their instruments. Perhaps also it is that we are typically more interested in what musicians do with their instruments—that is, the music that’s made with or for them—than we are with the instruments themselves. After all, books about architecture are unlikely to have much to say about hammers. Musical instruments and hammers are “merely” tools, and tools exist to serve some “greater” function in which we should supposedly be more interested.

As musicians gain experience, the instrument becomes simultaneously more and less important. More important because the performer gains confidence through familiarity with his instrument, confidence that it will respond as expected allowing him to communicate his musical ideas. But also less important because this familiarity renders the instrument invisible. David Sudnow notes that once a musician attains a certain competence “he may see past [the instrument] into the music with

a look that is hardly looking at all.” Klemmer, Hartmann and Takayama write: “One of the most powerful human capabilities relevant to designers is the intimate incorporation of an artifact into bodily practice to the point where people perceive that artifact as an extension of themselves; they act through it rather than on it.”

1.2 Inputs

Atau Tanaka provides this wonderfully pithy definition of what he terms a “traditional acoustic instrument”: It is “the object that the performer holds or plays on.” The instrument is defined in terms of a performer’s relationship to it; it is something that a performer does something with. This suggests that the action is where and how the instrument and performer meet. In this way a musical instrument is a kind of interface for performance. While digital controllers are often thought of in this way, acoustic instruments seldom are. Perhaps this is because with many acoustic instruments what might be thought of as interface elements are also the sound-making elements. The more usual case is for instruments to be considered on the basis of the means of sound production, wind or percussion instruments for example. This view certainly gets at something about how instruments produce sound, but looking at instruments in this way does not convey much in terms of how performers use them to make music.

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Taking a more human-centered, action-oriented view of instruments brings into view the kinds of information and energy exchange that happens between performers and their instruments that allow them to be expressive. Adopting this viewpoint, Tellef Kvifte suggests that when thinking about instruments we’re not usually concerned with the instrument as an object per se, but in how the musician uses that object to make music.⁵ He even proposes a taxonomy of musical instrument’s based on how performers control them to make music.⁶

Acoustic musical instruments act as transducers, converting the player’s physical energy into sound. As interfaces, instruments have points where the performer puts energy into the instrument in order to initiate or alter the sound: inputs. The inputs of these musical interfaces take such forms as mouthpieces, strings, buttons, keys, frets, valves, drum heads, pedals, etc., and an instrument’s particular selection and arrangement of inputs affords certain actions. For example, the mouthpiece of the clarinet affords blowing while its keys afford pressing with the fingers. The form of the clarinet is not, however, determined entirely by its interface—an interface which affords both button pressing and blowing need not look like a clarinet. The form of the clarinet is also determined by the material from which it’s made and the fact that its interface is directly coupled to the physics of its sound production.

It is not the case with all acoustic instruments that the physics of that instrument determines the disposition of the inputs, however. Obviously, this is often the case where the inputs act directly on the resonant bodies themselves, as with the clarinet or violin, but not so with an instrument such as

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the piano, where in normal performance the resonant bodies (i.e. the strings) are not directly manipulated by the performer. The keys of the piano do not themselves set the strings vibrating. Rather, through the piano’s action, the keys set a hammer in motion that in turn strikes the desired strings. The arrangement of the piano keyboard and placement of the pedals is therefore not directly related to the physics of the piano. In fact, there are keyboard arrangements other than the familiar piano layout, such as those found on different kinds of accordions. The layout of the keyboard must be determined by other human or conceptual/theoretical factors. Kvifte notes that to the pianist the keyboard arrangement is much more complex than a simple ascending ordering of pitches. Other music theoretical and performance specific factors determine how the keyboard looks (or feels) to the pianist, and the appearance is dependent on contextual factors, for example the key the pianist is playing in.\footnote{Kvifte, “Musical Instruments and Man-machine-interaction or Why Play the Tin Whistle When You Got a Synthesizer,” 12.}

Bodily engagement on the input side consists of posture and gesture. By posture here I mean interface in the most basic sense: how the performer’s body meets the instrument, or the way the performer positions himself with respect to the instrument. Posture is determined by the disposition of the inputs. And by virtue of being designed by and for humans, the disposition of the inputs is determined by the size and shape of the performer. Even for instruments where the physics of the instrument is acted on directly, mechanisms and technologies have been devised to put the inputs within reach of the performer. Take the keywork on most orchestral woodwind instruments, for example; systems of rings and axles allow the performer to open and close holes on the instrument that would otherwise be out of the reach of the player’s hands.
A given instrument will have a set of gestures associated with it. Recognizing that gesture in music is an enormous topic, for the moment my use of the term refers to the physical actions taken on an instrument’s inputs. These gestures are connected with the most basic affordances of the instrument and may fall into either the category of excitation gesture or modification gesture. An excitation gesture “is the one that provides the energy that will eventually be present in the perceived phenomena,” here the sound. A modification gesture essentially alters how the instrument responds to an excitation gesture. It should be noted, as Cadoz and Wanderly do, that in practice these gesture categories are not completely distinct from one another. For example, a violinist can alter the instrument’s response continuously with the bow, making the sound louder or softer, scratchier or whispier, etc. This categorization is, however, useful for distinguishing the most basic affordances for an instrument’s inputs, say a clarinet’s mouthpiece from its keys.

Some of these posture and gesture combinations are iconic and easily identifiable. If I want to conjure the guitar, I can stand with my left hand out to the side while making a strumming motion with my right hand. In his dissertation, Dan Trueman identifies a violin “superclass” that is defined in large part by how a performer engages with the instrument physically.  

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Different instruments demand different levels of engagement, or as Perry Cook put it, “Some players have spare bandwidth, some do not.” This “bandwidth” may be physical. How much of the body do the posture and gestures of performance require? The drum set engages all four of the drummer’s limbs, not leaving much physical bandwidth, while the trumpet player, as Cook notes, has bandwidth to spare.

Bandwidth may also be cognitive. This sort of mental bandwidth is not as easily quantifiable. The amount of mental effort required is a function not only of the instrument itself, but also the music being performed and possibly the performance context. On first thought it might seem that a polyphonic instrument such as the piano might require more bandwidth than a single line instrument such as the flute because the pianist has to deal with more than one line of music. But there are performance aspects that the flutist must attend to, such as adjusting intonation or finding places to breathe, that the pianist does not have to deal with. The physical requirements of playing an instrument are observable, while the mental requirements are more difficult to quantify.

1.3 Outputs

To the naive observer, the act of playing a musical instrument is fairly one-directional: a player does something (bow, blow, hit) to an instrument and that instrument makes a sound. A clarinetist blows into the instrument, wiggles her fingers and, like magic, music (or at least sound) happens. While such a simplistic view tells us something about how the clarinet is played (the clarinetist does, in fact,
blow into the instrument and wiggle her fingers), it does not really tell us how it might be played well, or what the clarinetist experiences apart from blowing and finger wiggling that allow her to expressively control her instrument. For the performer, playing a musical instrument is an intensely interactive experience. What the naïve view presented above misses is the fact that, in addition to putting energy into the instrument’s inputs, the clarinetist is getting information back from the instrument.

As the performer plays, he is listening, thinking, and responding constantly. In performance, this interaction between performer and instrument happens incredibly rapidly and the iterative nature of the interaction forms what Bongers calls the “interaction-loop.”11 This interaction-loop between the human performer and the instrument consists of control and feedback: the performer exerts control and receives feedback from the instrument.

We get feedback from the tools we use, and that feedback helps us know how we’re doing. For example, the tighter the bolt gets, the harder it becomes to turn the wrench; this feedback lets us know that the bolt is getting tight. Part of the difference in knowing how a tool is used and in knowing how to use that tool to accomplish a task lies in understanding and interpreting the feedback the user gets via the tool. The better we get at using our tools, the more embodied this process becomes. Though she might not be thinking consciously about it, our imaginary clarinetist is relying on feedback from the instrument to help her make the best sound and to play as musically as possible.

The feedback that performers receive from their instruments is multimodal, that is, it comes from different senses. That the player relies on auditory feedback is obvious. But performers also rely on other types of feedback to help them know about the state of their instrument and their relationship to it. For some instruments, visual perception is very important to performance. In percussion, for example, visual feedback is crucial because for most percussion instruments the performer does not maintain physical contact with the instrument. Consider the five-octave concert marimba: the instrument is about eight feet long and that the individual bars are 1.5–2 inches wide. It would be very difficult to find the right notes without being able to look at the instrument, so the performer’s visual sense is extremely important. On the other hand, vision would seem to play no role whatsoever for the trumpet player because he can maintain his connection to the mouthpiece and the instrument’s three valves. Other instruments may exist between these extremes, with vision playing some role, though perhaps not a central one. For example, while the pianist can keep the fingers of one hand on the keyboard when playing within the span of about an octave, large leaps require moving the hands off the keyboard. Two factors that would seem to determine the importance of visual feedback are: whether or not the performer remains in constant contact with the instrument, and the physical size of the instrument. The less contact the performer maintains with the instrument, the greater the reliance on visual feedback; and the larger the instrument, the more likely that vision would play an important role.

For instruments where visual sense is not an important feedback path, the kinesthetic sense may very well be. The kinesthetic sense is the awareness of the body in space and motion. Through practice,
performers learn the physical dimensions and features of their instruments—one’s “way around” the instrument—by learning how their bodies feel when engaging with the instrument in different ways. The trombone provides a fairly obvious illustration of the importance of the kinesthetic sense, as trombonists are able to find discrete slide positions despite the slide being a continuous controller. Less obviously, pianists and keyboard percussion players are able to execute large leaps through a combination of kinesthetic and visual sense, the visual sense fine-tuning a target whose position was estimated kinesthetically.

Haptic perception consists of a combination of kinesthetic sense and tactile perception, which “receives its information through the cutaneous sensitivity of the skin, when the human is not moving.” As Berdahl points out, most traditional instruments provide the performer with haptic feedback through vibrations of the instrument itself. While some of the energy put into the instrument is radiated as sound, some of the energy is returned to the player as vibrations in the instrument body. These vibrations are an inherent feature of acoustic instruments because the sound of the instrument is caused by their mechanical vibrations, their “mechano-acoustic” coupling. Perry Cook observes that many “intimate expressive musical instruments [exhibit] blurred boundaries between player, controller and sound producing object.” This is due to the fact that with haptic feedback inputs and outputs are often the same thing, the violin string, for example.

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12 Ibid., 131.
In his article “Tactile Audio Feedback,” Chris Chafe notes that the cellist has five points of contact with the instrument—two legs, two hands and the chest—that can sense the motion or vibrations of the instrument. In the same article, he demonstrates that cellists should be able to distinguish transients from steady-state parts of the signal with their left hands through the vibrotactile sense.\textsuperscript{16}

Vibrations are also felt in wind players’ mouths and brass players’ lips, and the apprehension of these feedback cues likely aids performance.\textsuperscript{17}

Haptic feedback is given by the instrument through the transduction of excitation energy provided by the performer. The visual and kinesthetic feedback discussed previously, on the other hand, are entirely passive forms of feedback. They are not given by the instrument, but rather are discerned by the performer through the recognition of her location, position, or orientation with respect to the instrument.

Similarly, with most instruments the performer is able to recognize and regulate the amount of energy he or she is putting into the instrument in order to control aspects of the sound, often the amplitude. The sensations associated with exciting/playing the instrument constitute a form of feedback because the recognition of those sensations help the player to control his instrument. If the sound is too loud he can use less energy, or if it’s too soft he can use more. This knowledge and recognition of how the instrument will respond is a fundamental aspect of performance. As with


visual and kinesthetic feedback, this is not feedback given by the instrument per se. What is sensed is the physical effort required to overcome resistance put up by the instrument.\textsuperscript{18, 19}

Actually, in many cases this is not feedback at all, but rather feed-forward. Having learned through practice how the instrument responds to different levels of input energy, the performer has a pretty good idea how an instrument will respond to a certain input force. And equally importantly, the performer has developed a sense of how it feels to exert the level of energy required to elicit a certain response. Through this embodied knowledge, a performer gains an intuitive sense of what various dynamic levels feel like and can thus predictably recreate them reasonably accurately.

The various feedback channels that we’ve discussed can be more or less active depending on the nature of the instrument, its playing posture, method of excitation, etc., and while they are important, their importance is secondary to auditory feedback. An instrument’s inputs facilitate making and controlling sound. It is therefore unsurprising that auditory feedback would be the primary feedback source for the musician.


\textsuperscript{19} The resistance is a necessary function of the transduction of input energy to sound energy.
Auditory feedback of course comes directly from the instrument to the performer’s ear. Auditory feedback also comes from the acoustic space or room the instrument is being played in. Trueman makes the point that the reflected and filtered sound that comes back to the performer in an especially reverberant space, such as a bathroom, can overwhelm the direct sound of the instrument, in a way becoming part of the instrument. Experienced performers will adjust their playing based on the acoustic properties of the room, so even acoustic spaces less extreme than bathrooms are important sources of feedback.

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1.4 Completing the loop

The interaction- or feedback-loop is completed by the brain. The information from all of the different feedback channels is processed by the brain, which instructs the relevant muscles to make adjustments to the input that the performer is giving the instrument. However, experienced musicians do not conceive their instruments in terms of inputs and outputs. The interaction loop connecting inputs and outputs via the brain constitutes a more familiar concept to the musician: technique.

Technique is not the end goal for performers. Rather, technique facilitates the goal of making music. If, as Marc Leman suggests, the instrument is “the technology which mediates between human mind (musical ideas) and physical energy (musical as sound),”\(^\text{22}\) then technique renders that mediation possible. Sophisticated musical interpretation requires sophisticated technique, and the subtlety of expression afforded by highly developed technique facilitates more subtle musical interpretation. Of course, musical interpretation is a learned skill just as technique is, so it makes sense that musical and technical development generally happen in parallel.

In his book *Things that Make Us Smart*, Donald Norman identifies two modes of cognition that are relevant to musical instruments and musical performance: experiential cognition and reflective cognition. Experiential cognition, he says, “is the mode of expert behavior, it is a key component of efficient performance.” Reflective cognition, on the other hand is the mode of “comparison and

contrast, of thought, of decision making.” While experiential cognition might dominate expert performance, it is hours and hours of more reflective work that build the technique that makes fluent performance possible.

In fluent performance, the instrument should ideally be invisible to the performer. When, in performance, a musician finds himself playing music as opposed to playing an instrument, the instrument has become, to use the Heideggerian term, “ready-to-hand.” When a tool is ready-to-hand, the focus of the user is on the task he is carrying out with the tool, rather than the tool itself. In this state, the performer’s activity is making music and the instrument mediates between the mental conception of the performer and the sound. The performer acts through the instrument rather than on it.

This is an aspect of “flow,” which Csikszentmihaly describes as “the state in which people are so involved in an activity that nothing else seems to matter.” In the state of flow “action and consciousness […] become one.” Of course, there are more variables in a flow state than just the musician and his instrument, including “the acoustic space, the social setting and other providers of context.” A tool’s being ready-to-hand is in contrast to it being “present-at-hand,” where the tool itself is the object of focus.

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1.5 On expert performance

One might use the term virtuosity to describe expert behavior. Bob Ostertag describes virtuosity as a sort of physical intelligence gained over time:

[Virtuosity is] what happens when someone acquires such facility with an instrument or paintbrush, or with anything physically manipulable, that an intelligence and creativity is actually written into the artist’s muscles and bones and blood and skin and hair. It stops residing only in the brain and goes into the fingers and muscles and arms and legs.28

Ostertag’s definition captures the visceral, embodied nature of the intelligence necessary for fluent performance, while extending the idea to include an element of creativity that comes with that knowledge. Daniel Levitin reckons that it takes approximately 10,000 hours to achieve the sort of deeply embodied expertise and creativity that Ostertag describes.29, 30

To dedicate that much time and energy to developing one’s skills would seem to require more than merely wanting to play music. Charles Rosen writes:

Pianists do not devote their lives to the piano simply because they like music… There has to be a genuine love simply of the mechanics and difficulties of playing, a physical need for the contact with the keyboard, a love and need which may be connected with a love of music but are not by any means coincident with it.31

The idea here is that the interface itself—the instrument—should resonate with the player. In order to become a virtuoso, one must really like the way one’s body interacts with the instrument and the sensations one gets from it.

29 Daniel J. Levitin, This Is Your Brain on Music: The Science of a Human Obsession, First Thus (Plume/Penguin, 2007), 197.
30 Malcom Gladwell also talks about this in Malcom Gladwell, Outliers: The Story of Success, Reprint (Back Bay Books, 2011).
Instruments have a cultural heritage. Even non-violinists know something about how a violin works and how it should sound by an early age because the violin occupies a certain place in Western culture. There is a clear sense of what it means to be an expert on the violin. The sonic characteristics of expert violin playing are well established, as are techniques for achieving that sonic ideal. This is not the case for novel instruments. Mark Applebaum writes of wanting to define what virtuosity would entail on the Mousetrap instruments he invented. This is not a problem for an aspiring violinist; there is no shortage of excellent violinists to emulate. Performers, like Mark Applebaum, who are the only performers on their chosen (or invented) instrument are simultaneously the world’s best and world’s worst whatever-ist. A situation that he notes is both inspiring and daunting.

1.6  Technique and idiomaticism

Instrumental technique exists on several levels. At one level is the sort of technique that concerns the mechanical operation of the instrument, the connection of inputs and outputs described previously. But musical instruments are not only defined in terms of their inputs and outputs, or even the sounds they make, but also by the music that is made with them. There are, of course, instrumental techniques that play a role in defining instruments musically.

Of technology in general Donald Norman writes, “each technology has properties—affordances—that make it easier to do some activities, harder to do others: The easier ones get done, the harder

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neglected.” With respect to musical instruments, the activities that are easier to do might be said to be idiomatic. When discussing the notion of affordance with respect to musical instruments earlier, I used the example that the clarinet’s keys afford pressing. While obviously true, that observation doesn’t consider that certain combinations of keys, or transitions from one fingering to another are likely to be easier than some others. The idiomatic ones are the easier ones. Each instrument has an idiomatic gestural language that is established by the relationship between performer and instrument. This gestural language is created, in part, by the way the player’s physiology engages with the instrument’s inputs.

In their study on idiomaticism, Huron and Berec make this connection between “affordance” and idiom. They cite an example from Donald Norman’s The Design of Everyday Things where Norman suggests that a well-designed door will have affordances that tell the user how to open it, i.e. whether to push or pull. Huron and Berec note, “the idea is that an object provides latent action possibilities and that the perception of an object may entail the apprehension of certain functions.”

It is interesting that instruments from different musical traditions with similar affordances have evolved different modes of playing, suggesting that, in some cases, a general instrument design concept is robust enough to support several “action possibilities,” only some of which may be used by any given culture or musical style. In this case, the musical culture plays a significant role in guiding technique or performance style—the techniques evolve to serve the culture’s music and vice versa. The guitar serves as a good illustration of this. Many styles of music have their own idioms for

33 Norman, Things That Make Us Smart, 243.
the guitar (Flamenco, country, metal, etc.) which are distinct from one another, yet which all seem to be equally “of the guitar,” i.e. supported by the guitar’s “latent action possibilities”.

Not all idioms inhere to the performer/instrument interface. Even when considering idiomaticism with respect to a particular instrument in a particular musical style, idioms that are clearly learned—and not inherent to the interface—become part of the picture. Such gestures may not necessarily be idiomatic when considered strictly in relation to the mechanics of the performer/instrument interface, but they have been practiced to the point that they have become part of the performer’s natural language on the instrument. Fiebrink encountered this situation in her attempt to model flute fingering difficulty. Her model was unable to account for transitions that, while mechanically difficult, have been practiced to the point that they no longer present a challenge to the proficient human flutist.\(^{35}\)

One reason such gestures become well practiced is that they appear frequently in the repertoire. Repertoire can thus suggest certain common figures or gestures that get emphasized through instrumental pedagogy (scales being a quite obvious and basic example). An instrument’s repertoire influences the way that instrument is taught, and the way the instrument is taught may in turn feed idioms back into newly created repertoire. Gjerdingen suggests this idea in a commentary to the Huron and Berec article cited above.\(^{36}\)

\(^{35}\) Rebecca Fiebrink, “Modeling Flute Fingering Difficulty.” (Senior Distinction Project in Music, The Ohio State University, 2004).

Repertoire might also suggest changes to the instruments themselves, for example the change in bridge shape and height of bowed string instruments that occurred around the turn of the 19th century, or the change in bow shape.\textsuperscript{37} Such alterations in instrument design change the idioms as well. In the case of violin bows and bridge shape, whereas it was once possible—idiomatic even—to sustain three notes simultaneously, that is not the case on modern instruments.

\section*{1.7 The Audience}

Musical instruments are the mechanisms by which performers translate musical ideas into sound. Those ideas are ultimately communicated to an audience. In his essay “Communication, music, and speech about music” Steven Feld defines musical communication as “a socially interactive and intersubjective process of reality construction through message production and interpretation.”\textsuperscript{38} Messages are produced by performers and interpreted by audience members. He leaves quite open just what might constitute those messages, or how they might be interpreted. For him, the idea is not about communicating a specific meaning, but rather that communication happens at all.

In his book \textit{Embodied Music Cognition and Mediation Technology}, Marc Leman suggests that among the things that music communicates are its “moving sonic forms.” These moving sonic forms consist of “form relationships without defined meanings, just like architecture and dance. A building, for example, does not mean something; it just shows its formal structure.”\textsuperscript{39} In other words, at the very

\begin{thebibliography}{9}
\bibitem{37} Trueman, “Reinventing the Violin [and] Machine Language.”
\bibitem{39} Leman, \textit{Embodied Music Cognition and Mediation Technology}, 17.
\end{thebibliography}
least, music communicates its own form, and that form, in and of itself, constitutes meaning. Leman is careful to acknowledge that this is not the only possible meaning one can draw from music, but that this sort of meaning is understood without any additional cerebral processing, linguistic interpretation, or any notion of cultural meaning. Instead, “moving sonic forms” are understood by the body through physical action. Leman writes, “the physical energies of the music correspond with a physical disposition caused by being human… Gestural language of music is universal, because its moving sonic forms share human corporeality.”40 People understand music made by other humans at some visceral level by sheer virtue of the fact that they are humans as well.

Communication happens between all of the “social actors” involved in the presentation and reception of music: performers, audience members and composers (where applicable). In all of these cases, the musical instrument is the conduit through which this communication occurs. For the audience, the understanding of instruments and how performers engage with them is an aspect of Leman’s notion of “human corporeality” and provides an avenue for communication or understanding, particularly if the instrument being played is one that the listener is familiar with.

To an audience, an instrument may seem to be an extension of the performer’s body. This is a facet of Leman’s theory of embodied cognition. The performer is transmitting “both sonic and visual energy to the listener, who, through mirror processes, can make sense of it.”41 This is not necessarily to suggest that audiences will play air guitar through a concert (though some might), but that seeing and understanding, or even sympathizing with a performer’s physical actions helps listeners to

40 Ibid., 21.
41 Ibid., 161.
understand the music. In this visual transaction between performer and listener, the instrument is the locus of, and perhaps even part of the performer’s movements and actions.

It seems likely that the extent to which the instrument is part of the performer’s movements would influence the “oneness” of instrument and body that performers experience and listeners perceive. Instruments that can really move with the player, the violin or clarinet, for example, appear to be extensions of the performer. Less so the cello or double bass. When speaking of the double bass, Edgar Meyer interestingly inverts the instrument–performer oneness. Of his relationship to the bass he said, “The bass doesn’t appeal to me. I am the bass.”42 Visually, the bass does obscure much of the performer’s body, so even though it’s clearly not what he meant, there’s a sense in which his statement might ring true even for the audience.

Of course, when music is presented via an audio recording, there is no communication of “visual energy.” Nevertheless, audience members retain a knowledge and understanding of musical instruments from previous experiences. Feld writes: “Experience is not only cumulative; it is interactively so. We rarely confront sounds that are totally new, unusual, and without some experiential anchors. Each experience in listening must connote prior, contemporary, and future listenings.”43 This suggests that we may still imagine and sympathize with the performers’ physical actions because we can create mental images of even unfamiliar instruments based on their similarity to instruments with which we are familiar, even when we can’t see them. Thus at least as far as the communication of moving sonic forms is concerned, cultural context is irrelevant. Understanding

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can happen through bodily engagement; “signification, most often, is just a matter of focus and direct involvement.”\textsuperscript{44} Godøy, Haga and Jensenius use the term “motormimetic sketching” to describe the playing of air instruments and other physical activities that contribute to a corporeal understanding of the music.\textsuperscript{45}

Listeners might even be more likely to engage in “mirror processes” or “motormimetic sketching,” like air guitar, when listening as opposed to watching, in order to create or enhance the physical connection to music. The listener’s physical actions may in some way substitute for the lack of visual stimulation, or be an attempt to gain a corporeal understanding. People seek to engage with music this way because there is something pleasurable in engaging with music through “activities that require high-level motor skills.”\textsuperscript{46} The physical connection to moving sonic forms is pleasurable, even when the performers aren’t present.

\textbf{1.8 Moving forward}

The relationship between the expert performer and his instrument is very intimate by virtue of his having spent so much time with it. The relationship is dynamic, going beyond the “athletics of technique”\textsuperscript{47} to facilitate communication, or the transduction of a musical conception to musical sound. Knowing just how his instrument will respond is a source of confidence for the performer.

\textsuperscript{44} Leman, \textit{Embodied Music Cognition and Mediation Technology}, 18–21.
\textsuperscript{46} Leman, \textit{Embodied Music Cognition and Mediation Technology}, 18.
\textsuperscript{47} Tanaka, “Musical Performance Practice on Sensor-based Instruments,” 369.
The purpose of the preceding text was to establish a framework for discussing instruments on the basis of performers’ relationships with them so that we may then look at how those relationships are changed by mechanisms, technologies, or techniques that alter an instrument’s behavior or the performer’s experience of the instrument.

If the added technology is to be controlled by the performer, this raises important questions about how the existing instrument’s interface can be altered or augmented to support the new functions. What effects do those alterations have on the input side? Altering an instrument’s behavior will invariably affect the feedback the performer receives. How does the intervening mechanism change the performer’s experience? What sonic or musical possibilities does the performer gain in the process? And how do those changes affect the other parties involved in the musical transaction?
2 Altering the instrument

Musical instruments can be altered in any number of ways. Some alterations are so common that they are accepted almost as part of the instrument, and neither the performer nor audience thinks twice about them. Brass mutes might be considered in this category. Audiences are not likely to be surprised by either the sight or sound of a muted trumpet. As far as the audience is concerned, a mute might make the trumpet sound a little different, but it’s still a trumpet. The trumpet player experiences the change in sound color too, but he is also receiving feedback on other channels, making adjustments to how he is playing the horn and what he’s paying attention to. The resistance of air through the horn may feel different. The horn’s intonation may change forcing him to attune more closely to other musicians to avoid sounding out of tune. He may want to adjust his technique in order to heighten the mute’s effect. In short, what may appear to the audience as a rather minor change can have a significant effect on how the performer experiences playing his instrument.

Amplification is another sort of alteration that may seem innocuous, but which can alter the performer’s experience quite radically. Of course, we know that amplification can make things louder, but we don’t always think about how it changes the experience of an instrument beyond that. The sound of an instrument can be changed fairly dramatically through amplification. For instance, using a bridge pickup on a violin essentially removes the effects of the instrument body from the sound. An amplified acoustic instrument sounds different than its un-amplified counterpart. Furthermore, for the player the sound of the instrument is dislocated from the instrument itself. Whereas the sound normally comes from the instrument when played acoustically,
the sound seems to come from somewhere else when amplified. This forces the player to listen to himself almost like he would another player, undermining the intimate connection he normally has with his instrument.

Of course, alterations may be much more specific than those described above. In the text that follows the piano will be used as a case study for looking at specific alterations and their musical effects both for performer and audience.

2.1 The Piano

The piano has eighty-eight keys painted black and white with two or three pedals as the outside operators. Each key has only two states: on and off. The pedals work invariably over the whole region. Timbre is neglected. Also, there is no place for local variation of parameters (the fluctuation of a sound after initiation).48

The range of expression virtuoso pianists are able to achieve is remarkable considering how few expressive tools they actually have to work with. Played “normally” the pianist doesn’t actually touch the piano’s strings. He presses keys that through mechanical linkages cause a hammer to strike the strings. Once the hammer strikes the strings, there is nothing the pianist can do to alter the sound other than to make it shorter. And while it seems to be a source of debate among pianists and piano pedagogues, the hammer only knows how hard the key was struck, not the manner in which it was stuck. Apart from the sound of the pianist’s fingers hitting the keys, there is no distinction between

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legato and staccato attacks; the pianist cannot alter the articulation of a note.\textsuperscript{49} Timbral variation of individual notes is not possible either, except as a function of how hard the note is struck. Thus the primary expressive dimensions the pianist has to work with are loudness (how hard the key was struck) and duration (how long the damper is off of the strings).

It is perhaps due to the piano’s limitations that composers and pianists have sought new sounds from the piano and new ways of engaging with it. In this area, the piano’s limitations are actually a benefit. The relative isolation of the performer’s actions from the resonant bodies of the piano, coupled with the fact that pianos are free-standing and (grand pianos at least) have their resonant bodies easily accessible, make the piano particularly well suited to experimentation along a couple of distinct, though not mutually exclusive, paths: The pianist may change how he engages with the instrument, or he may change the instrument itself.

\subsection*{2.2 Cowell}

By changing how the pianist engages with the instrument, the piano’s resonant bodies may be excited in alternative ways. This idea was famously explored by Henry Cowell in his pioneering works \textit{The Banshee} and \textit{Aeolian Harp}. In \textit{The Banshee}, Cowell asks the pianist to rub and scrape the wound strings of the piano’s low register in different ways, using his hands and finger nails with the sustain pedal depressed throughout. Scraping along the length of the string creates a shrieking sound.

while rubbing the strings perpendicularly creates a glissandoing rumble. Punctuating the rumbling, shrieking texture created by the above described techniques are more clearly pitched melodic fragments created by plucking individual strings. Sonically the work is quite unpianistic. From a performance standpoint the piece is unpianistic as well, as the pianist must stand in the crook of the piano, reaching inside, as opposed to sitting at the keyboard.

_Aeolian Harp_ employs a similar technique to _The Banshee_, namely sweeping the strings with the fingers, but is quite different in musical affect. Whereas _The Banshee_ deemphasizes the pitched-ness of the piano to a great degree, _Aeolian Harp_ is a quite tonal. The pianist silently holds down chords on the keyboard while sweeping across the strings allowing certain notes to sustain but keeping others damped. The effect is quite similar to the autoharp, a strummed zither with buttons that when depressed dampen all of the strings except those needed for the desired chord. The resulting sound is rather raspy in its attack, but with a clear, harmonic sustain.

In both pieces, the strings themselves are used as the primary input device. _Aeolian Harp_ recasts the function of the keyboard as a “pitch selector” rather than a note initiator. The harmonic vocabulary and specific chord voicings are still very much of the piano. It is only the manner in which those harmonies are articulated that is novel. _Aeolian Harp_ thus builds on and extends the expressive capabilities of the piano and exists more comfortably in the continuum of piano repertoire. _The Banshee_, on the other hand, represents a complete re-imagining of the instrument. It is really only a piano piece in the sense that it uses a piano. Both in terms of its sound world and the performance
techniques used to create it, the piece has very little to do with the piano as it was known or used before. In fact, Cowell used the term “stringpiano” to refer to the piano’s being used in this way.\footnote{Maria Cizmic, “Embodied Experimentalism and Henry Cowell’s The Banshee,” \textit{American Music} 28, no. 4 (2010): 438.}

\subsection*{2.3 Cage}

In his works for prepared piano, John Cage leverages the fact that the resonant bodies of the piano can themselves be altered without affecting the performer’s interface. Cage cites Cowell, with whom he studied, as an inspiration for this line of thinking. Cage’s preparations of the piano involve the insertion of materials between strings of the piano—bolts and screws of various sizes and types, pencil erasers, felt, bamboo, pieces of rubber, coins—to create a staggering variety of timbres, from gong- and drum-like sounds to more subtle detuning and buzzing effects. The effect of a specific preparation is determined not only by the quality of material, but also the object’s placement along the length of the strings and the mass of the objects used. The number of variables involved makes it nearly impossible to characterize all of the possible sounds of the prepared piano.\footnote{Richard Bunger, \textit{The Well-prepared Piano}. (Colorado Springs, Colorado: Colorado College Music Press, 1973).}

What Cage wanted to achieve with the preparations was nothing short of a complete transformation of the piano. He writes: “The total desired result has been achieved if, on completion of the preparation, one may play the pertinent keys without sensing that he is playing a piano or even a ‘prepared piano.’ An instrument having convincingly its own special characteristic, not even suggesting those of the piano must be the result.”\footnote{From the score for Cage’s \textit{Amores}, as quoted in Ibid.} Cage’s preparations certainly transform the sound of the piano, but the piano’s outward appearance remains unchanged, as does the way the pianist
engages with the instrument. While prepared piano is often placed under the general rubric of extended piano techniques, it is not the pianist’s techniques that is extended, but rather the instrument itself. This lends an incongruity to live performances: What appears to be a pianist normally playing a piano sounds like a percussion ensemble. The sight of the piano does not jibe with the sounds emanating from it.

Listening to works for prepared piano while following the score is similarly incongruous. With the prepared piano, standard pitch notation is really just a tablature, with little or no relation to the resultant sound. There is no way to conjure a sonic image of the piece merely by looking at the score without having first become familiar with the sounds represented by the notated pitches. Similarly, the early stages of learning a prepared piano piece must involve teaching the ear how the piece sounds as much as teaching the fingers where to go. Since notated pitches correspond only to locations on the keyboard the resulting sounds seem, at least in the beginning, to be arbitrary.

Of this connection between physicality and notation that performers develop, Elisabeth Le Guin writes: “perusal of the score becomes anticipatory kinesthesia, a sub-verbal, sub-intellectual assessment of questions such as, What do I need to do in order to play this? Where will I put my hands, and how will I move them?”53 This much is maintained with prepared piano. Of course, in addition to the physical indications, notation typically also gives the performer a sense of how the

music will actually sound.\textsuperscript{54} When an instrument is altered such that it doesn’t respond as before, as with the prepared piano, that mental connection between notated pitches and sonic image may be short-circuited.

While certain aspects of the overall “sound” that notation captures are maintained—rhythm, density and dynamics, for example—the sense of pitch is not. With the prepared piano, the alterations to the instrument may obliterate the sense of pitch entirely, turning the piano into a collection of unpitched percussion instruments. After such a radical remapping pitch notation represents only a set of physical shapes and locations rather than also anticipating the pitches that result. In contrast, the use of a capo on a guitar represents an alteration of that instrument, but a much less cognitively disruptive one in terms of the performer’s relationship to notation. With a capo the open strings are altered, but the relationships between them are maintained. Thus both the sonic image and actual sound of a notated chord would be of the same type, differing only in their transposition. Scordatura tunings for stringed instruments represent a similar, but more disorienting, case to the capo as the relationship between the strings is no longer maintained. Unlike with the prepared piano, the disruption of the connection between notation and sonic image created by scordatura tuning does not obliterate the connection with pitch, but rather rewires it for some, though not necessarily all, strings.

\textsuperscript{54} Cizmic, “Embodied Experimentalism and Henry Cowell’s The Banshee,” 441.
For the composer interested in knowing how his prepared piano piece will sound ahead of time, the composition process would seem to necessitate the composer actually playing with the instrument and transcribing where his fingers went. In this case, the act of putting music for prepared piano into standard notation is as much a process of transcribing physical gestures as it is an effort to prescribe a particular sound concept. On the other hand, the composer may begin with notated gestures and allow himself to be surprised by the way those gestures are rendered in sound. In either case, the keyboard is essentially remapped; the question is whether or not the composer is concerned with the particulars of the new mapping. Regardless, the compositional act is one of discovery.

2.4 Crumb

The paradigms represented by Cowell and Cage—altering the performer’s technique vs. altering the instrument itself—are not mutually exclusive. Indeed, works like George Crumb’s *Makrokosmos vols. I and II* combine new piano techniques, preparations, and traditional techniques, expanding the sonic palette of the piano yet further. In Crumb’s hands, the piano can sound like an ensemble of different, even unfamiliar instruments as in “The Phantom Gondolier,” from *Makrokosmos I*. For that movement, the pianist is instructed to place thimbles on the forefinger and middle finger of his right hand which he uses to scrape or hammer the strings. The metallic sounds created with the thimbles are layered with notes played normally from the keyboard, harmonics played from the keyboard, as well as vocalizations from the pianist. The various piano techniques have distinct timbral identities, and Crumb gives each its own musical character. Leveraging pianists’ ability to
realize complex contrapuntal textures, Crumb layers the different voices in a way that creates the illusion of multiple independent instrumental parts, turning the piano into a small ensemble.

Throughout the *Makrokosmos* pieces, the pianist’s hands move back and forth between the keyboard and the inside of the piano. As Maria Cizmic notes in an article about *The Banshee*, from the audience perspective there is a certain sense of mystery created whenever a pianist reaches inside of the piano. While the audience can see that the piano is not being played in the “normal” way, it isn’t apparent just what the pianist is doing because his hands are obscured by the instrument. To really understand how the sounds are made requires that the listener/viewer know something about the inner workings of the piano. Even then, without being able to see what he’s doing to the piano’s inner workings the sounds remain somewhat mysterious. If the audience cannot see clearly the pianist’s actions, or what it is he’s acting on, the piano becomes, quite literally, a black box.

2.5 **Player Pianos and their variants**

All of the previously discussed pieces have in common the fact that it is the pianist who creates the sounds. That is, the energy used to create the sound is transferred from the pianist to the piano. Systems for automatic piano performance have existed in one form or another since the mid-nineteenth century. Before the advent of recording technology, these systems were used primarily as a way of recreating performances of existing piano repertoire. In the twentieth-century, however,

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55 Ibid., 449.
some composers became interested in the compositional possibilities that the super-human accuracy of devices such as the pianola, Disklavier and other one-off robotic systems afforded. Stravinsky dabbled with the pianola. Finding it well-suited to executing extremely complex canonic relationships, Conlon Nancarrow composed for it almost exclusively. More recently, in his work Quadrturen III, Peter Ablinger used a computer-controlled player piano to render nearly intelligible speech (at least with the aid of subtitles) through the piano.

For the most part, these systems take the pianist out of the equation, and that’s largely their point. Player pianos are able to execute things far beyond the capabilities of any human performer, but they typically still do so using the hammer action of the piano. In this sense, they represent more an extension of traditional pianism than an expansion of the sonic capabilities of the instrument. The pneumatic and electromechanical technologies that these systems use to engage the hammer action of the piano can be viewed as ersatz pianists.

2.6 Actuated Pianos

Exciting the strings directly, though through means other than the transfer of energy from pianist to piano represents an extension of the Cowellian paradigm. In his 1966 piece Wave Train David Behrman used acoustic feedback to excite the piano strings. According to Behrman’s liner notes, he and Gordon Mumma placed guitar pickups on the piano strings and, via an amplifier, routed their outputs through a loudspeaker back into the piano. Over the course of the piece, the amplifier gain
is raised and lowered, creating waves of sound. The texture and timbre of the waves is varied by moving the pickups to different locations in the piano, picking up different strings and different harmonics. The pickups themselves vibrate against the strings, adding to the din.\textsuperscript{56}

The acoustic feedback used by Behrman was brought into the popular consciousness by electric guitarists such as Jimi Hendrix. Related to the concept of acoustic feedback is The EBow, a commercially produced, hand-held device that was designed to allow electric guitarists to “bow” the steel guitar strings using electromagnets.\textsuperscript{57} Composers and researchers have discovered that the steel strings of the piano can be similarly actuated.

Stephen Scott is a pioneer in coaxing unusual sounds from the piano. The Bowed Piano Ensemble which he founded uses bows fashioned from rosined lengths of fishing line, tongue depressors with horse hair, and other improbable objects to play inside the piano. For his solo piece \textit{Resonant Resources}, Scott uses what he describes in a 2005 interview for newmusicbox.org as “the equivalent of having 12 EBows on a chromatic octave of the piano” to actuate the piano strings.\textsuperscript{58} The technique Scott employs for about the first two thirds of the piece focuses the listener’s attention more on the release of notes than the attacks, inverting, in a way, the normal way of hearing the piano. Scott silently depresses the keys allowing the strings driven by the actuators to resonate. This creates attacks that are relatively slow because the sound is initiated by the actuators, not the hammers. The

\textsuperscript{58} A transcription of the interview is available at: http://www.newmusicbox.org/assets/71/interview_scott.pdf
releases of the actuated notes and chords are done in such a way that the vibrating strings are allowed to buzz briefly against the damper, creating moments where the sound is much more harmonically rich. These moments punctuate the otherwise smooth texture, drawing attention more to the releases of the notes than the attacks. The last third of the piece features repeated downward glissandos that create a shimmering, ethereal texture within which certain notes and chords resonate more strongly.

In her 2001 piece *Holding Pattern*, Maggi Payne calls for three EBows to be used inside the piano. The EBows are kept on the same three notes throughout the piece and the emergence of the actuated notes is meant to be a surprise to the audience—Payne asks the performer to be as discreet as possible with the placement of the EBows and requests that they not be mentioned in any program notes. The sustain of the EBow chord emerges out of a chromatic cluster struck to begin the piece. Once they’re sustaining, the piece proceeds as a series of manipulations of the sustaining chord. Slowly releasing the sustain pedal creates a texture of shifting overtones, and as the piece continues, notes of the chords are removed leaving only the highest note of the chord. The piece evaporates with a quiet string glissando performed inside the piano and the decay of the highest chord notes.

### 2.7 The Electromagnetically-Prepared Piano

What follows is an extended discussion of two electromagnetically actuated piano systems. For each system, technical information is given about the system generally, followed by a discussion of works composed for each respective instrument. While the two systems are similar in the sense that both
use electromagnets to vibrate the piano strings, there are important differences in how the composers/researchers view and use their respective systems. These differences are manifested both in the design choices that went into the systems, and in the music composed for them. While both systems endow the piano with new capabilities, it is interesting to consider the pianist’s roles in the different pieces (if there is a pianist at all) in terms of their engagement with—or detachment from—the abilities afforded by the electronics. The performer interaction (or non-interaction) with the new features may fall into any of the patterns identified in the previous discussion of canonical works by Cage, Cowell and Crumb. Namely, the transformation of instrument with no required change in technique (Cage), the use of new techniques (Cowell), and both of the above (Crumb). The two systems are compared side-by-side in Section 2.11 below.

The Electromagnetically-Prepared Piano, developed by Berdahl, Backer and Bloland,59–60 consists of twelve electromagnetic actuators attached to a rack that sits inside the piano. The rack is designed such that the individual actuators can be positioned anywhere across the range of the keyboard, and installation does not interfere with the normal hammer action of the piano. Each actuator is connected to its own amplifier channel, and each amplifier channel has a dedicated DAC channel feeding it audio generated in Max/MSP. The audio channels can be addressed individually or all twelve simultaneously.

The actuators in the Electromagnetically Prepared Piano are analogous to loudspeakers. Audio is synthesized in Max/MSP or some other environment and sent via a DAC and amplifiers to the actuators, causing the strings (as opposed to a speaker cone) to vibrate. The strings will respond to their fundamental frequencies, and harmonics up to about the tenth partial are also available. With their twelve actuators, the researchers can theoretically cover the entire range of the piano using overtones. The audio signals driving the actuators need not be harmonic, however. The researchers mention the use of filtered noise as well as recordings of speech sounds as potential source signals. In the latter case, it is much more effective to send the same audio signal to all twelve amplifiers. The Electromagnetically-Prepared Piano has been used by Per Bloland in three pieces: Elsewhere is a Negative Mirror, Negative Mirror Part II, and Of Dust and Sand.

2.7.1  Elsewhere is a Negative Mirror

Elsewhere is a Negative Mirror, Bloland’s first work for Electromagnetically-Prepared Piano, is a solo for that instrument. The electromagnets create a hazy, ethereal, often shimmering sound, quite unlike the normally articulated piano those sounds accompany. The piece begins with the pianist striking notes on the piano and the magnets picking up that sustain. This, however, is the only section of the piece where it seems that the player is in control of, or causing the behavior of the electromagnets.

For most of the piece, the pianist’s part and the computer-generated electromagnetic part proceed independently of one another. The performer uses a foot pedal to select preset functions for the magnets, which then run on their own. The electromagnets create pulsing chords and arpeggiations.
using filtered noise, and glissandos between harmonics above chord tones using square waves.

Between sections of the piece, the pianist silently depresses the relevant piano keys and then uses the sostenuto pedal to ensure that those strings are free to vibrate. The distinction between the various electromagnetic textures can be rather subtle because the natural decay of the piano strings has the effect of rounding off any sharp edges.

The introduction not only reveals the function of the electromagnets—and the apparent new behavior of the piano—but also the pitch material for the electronic part. The pitches of the electronic part are determined by the placement of the actuators (Figure 2.1). The fundamental and overtones of the twelve notes that the actuators are positioned over are available, but different sections of the piece use subsets of the available pitches. Pitch material is not restricted so much in terms of the pitch classes that are available—all twelve pitch classes are possible either as fundamentals or overtones—^\textsuperscript{61}—but the registers in which a given pitch class can appear become highly restricted.

\begin{figure}[h]
\centering
\includegraphics[width=0.7\textwidth]{figure2_1.png}
\caption{Placement of actuators for Per Bloland’s “Negative Mirror” pieces.}
\end{figure}

\textsuperscript{61} Harmonics up to about the tenth partial are available. Ibid., 126.
The pitch material that is available for any section is further restricted by the physical limitations of the pianist. To prepare the actuated notes the pianist silently depresses the relevant chords and then depresses the sostenuto pedal, allowing those strings to vibrate freely as long as the pedal is depressed at the beginning of each section. While there are twelve actuators, the pianist only has ten fingers, so at most only ten pitches may be sustained simultaneously using the sostenuto pedal. Furthermore, not all combinations of the twelve available strings are possible for the pianist to grasp given their location on the keyboard. The chords must fit into the pianist’s hand. An example from the piece is given in Figure 2.2.

Figure 2.2 Sustained chord and sounding pitches figures 2 and 3 of Per Bloland’s Elsewhere is a Negative Mirror. The partial numbers show the strings on which the sounding pitches are produced. Open noteheads are the sounding pitches and round (as opposed to diamond) noteheads show the string.

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62 This is an underappreciated fact about the piano and instruments in general. The piano has 88 keys, but due to the pianist’s physiology not all combinations are available at any instant. In fact, every instrument has similar limitations on what’s possible/practical imposed by the disposition of the inputs and the way the body engages them.
For Bloland, these restrictions provide something to work against compositionally. While the piece begins with the pianist articulating the same pitches as the magnets (or vice versa), the trajectory of the pianist’s part is a gradual move away from that pitch world. As a result, Bloland seems to be able to play with the resonance with the piano. When the pianist articulates one of the pitches sounding in the electronics, or an octave transposition thereof, the note seems to glow, taking on an unnatural sustain. Sometimes this is a result of the piano and electronic parts lining up by chance. In other cases, Bloland himself triggers notes manually on the laptop from a position in the audience in response to the piano part.\(^{63}\) The idea of resonance that Bloland plays with is further highlighted by the deliberate, strictly notated use of the sustain pedal. As the piece progresses it seems to become less about the actuators and the abilities they afford, and more about the acoustic qualities of the piano itself.

Indeed the piece ends with the pianist bringing out a single note from the haze of harmonic glissandos in the magnets. The timbral qualities of that note are then explored through various inside-the-piano techniques including scraping the strings with a coin and playing harmonics on the strings with the magnets silenced. Interestingly, once Bloland has sensitized our ears to these “other” sonic qualities of the piano through his use of the magnets, the magnets are no longer required for us to hear the piano in a different way.

\(^{63}\) This additional layer of activity is not indicated in the score.
2.7.2 Negative Mirror Part II

Compositionally, *Negative Mirror Part II* begins where *Elsewhere is a Negative Mirror* leaves off. Scored for electromagnetically prepared piano and a small instrumental ensemble, the piece begins with a short introduction featuring the electromagnets sounding on their own, after which the pianist picks up on the same technique of scraping the piano strings with a coin that ends *Elsewhere is a Negative Mirror*. Bloland describes the trajectory of *Negative Mirror Part II* as being opposite that of *Elsewhere is a Negative Mirror*: The instrumental ensemble and electromagnets begin in different pitch worlds, but gradually merge over the course of the piece.

While the electromagnets are not featured as prominently in *Negative Mirror Part II* as they are in *Elsewhere is a Negative Mirror*, they nevertheless hold similar musical and conceptual significance. After the introduction, it is almost four minutes before the magnets are heard again. When they finally do reappear, the magnets pick up notes of a chord articulated in the instrumental ensemble just prior. This entrance is not at all jarring, as the electromagnets are initiated by a struck piano chord. For much of the remainder of the piece, chord changes are initiated similarly, with the pianist striking single notes that trigger a response in the magnets. The music is in some ways paced by the magnets because they dictate the harmonic rhythm, and because of this, just as with *Elsewhere is a Negative Mirror*, the electromagnets in *Negative Mirror Part II* constitute an instrumental voice of their own, rather than functioning as an effect on the piano.
The musical treatment of the sustained chords varies. Sometimes the instrumental ensemble picks out resonances from the sustaining chord, amplifying or providing commentary on the slow moving harmonies. This is sort of the opposite effect of Elsewhere is a Negative Mirror, where struck piano notes were seemingly made to resonate; here the instruments highlight an ongoing resonance. In other sections, sustained chords in the electromagnets disappear in the background behind very active instrumental parts, almost becoming part of the acoustic space (Figure 2.3).

![Figure 2.3](image)

Figure 2.3 Except from Per Boland’s Negative Mirror Part II. The lines in the electronics part indicate the chords sustained by the electromagnets. The bracketed chords sound in response to the sforzando piano notes.64

Apart from triggering the electromagnetic chords, the pianist has very little to do over much of this nearly seventeen-and-a-half-minute piece, save for the last two and a half minutes. As the piece winds down, the pianist begins playing polyrhythmic chromatic figures that start in the upper register of the keyboard and gradually work their way down. These passages prefigure the concluding

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64 Score excerpts used with the author’s permission.
gesture of the piece, in which an audio file of an earlier section of the piece is played through all twelve electromagnetic coils simultaneously. Conceptually, this completes the convergence of the pitch world of the electromagnets and that of the instrumental ensemble: The sound of the instrumental ensemble is literally filtered by the electromagnets. Only those frequencies that are harmonics of the actuated strings (see Figure 2.1) resonate. When played through the piano, the audio file’s content is not recognizable as music that has come before, but the shimmering of upper partials seem like a strange echo of the preceding piano figures.

The electromagnets in *Negative Mirror Part II* are controlled by computer, with the pianist using a foot pedal to select different preset patches. The piece was originally written for Disklavier, the MIDI capabilities of which would be used to trigger the electromagnets in those places where a piano note seems to initiate sustained chords. In the absence of a Disklavier, Bloland admits in an email to the author that he sits “discretely in the front row with a score, the laptop and a 15’ firewire cable connected to the gear on stage.” From this position he triggers the magnets, creating the illusion that the electromagnets follow or respond to the pianist.

### 2.7.3 Of Dust and Sand

*Of Dust and Sand* is Bloland’s third piece for the Electromagnetically Prepared Piano. Scored for alto saxophone and Electromagnetically Prepared Piano, it represents a significant change in how Bloland conceives of the instrument both sonically and in terms of the pianist’s interaction with it. Bloland
uses preparations on the notes that the electromagnets affect, and copious saxophone multiphonics to create an otherworldly texture that buzzes and wheezes, by turns organic and mechanical.

To prepare the strings, Bloland calls for a plastic ruler to be laid across the strings in the lowest register, and a sheet of paper placed on the strings in the middle register. Both of these preparations are on notes affected by the electromagnets. He also calls for a small chain to be laid across the strings in the upper register, outside the range of the electromagnets. These preparations create buzzes of different colors, not unlike the buzzes associated with various African xylophones or thumb pianos, or even the kazoo. The preparations obliterate any sonic resemblance to the natural acoustic sound of the piano when the strings are actuated by the electromagnets. Bloland heightens the buzzy effect by driving the electromagnets with square waves.

The piano preparations are a new wrinkle in Bloland’s treatment of the instrument, and unlike with the “Negative Mirror” pieces, the pianist in Of Dust and Sand also interacts with actuated notes. One of the main piano techniques in the piece involves the pianist dampening the strings inside the piano with his fingers. When this technique is called for, the strings underneath the player’s fingers are actuated with the electromagnets. In order to sound a note the performer lifts his finger, allowing the strings to vibrate. By controlling the application and release of pressure on the strings, the performer can shape the both the attack and release envelopes of the sound. Notes sound quickly if the finger is lifted all at once, but the sound is still unlike that of a piano struck normally. Without the transients resulting from the hammer striking the strings, these notes can sound almost like a piano note played
backwards. This technique is called for with the highest seven actuator notes. Bloland devised a tablature notation that uses one line for each finger and normal rhythmic notation to show how notes should be released (Figure 2.4).

![Tablature explanation](image)

**Figure 2.4** Tablature explanation from Per Bloland’s *Of Dust and Sand*.

In the “Negative Mirror” pieces the pianists’ parts and the electromagnetic parts exist on parallel, but separate tracks. In *Of Dust and Sand*, the two parts seem more integrated thanks to the finger dampening technique. As with the “Negative Mirror” pieces, the pianist in *Of Dust and Sand* uses a foot pedal to select preset functions that determine the behavior of the actuators. In that role, the pianist manages how the system functions, but without determining what those functions are. However, with the finger dampening technique the performer is also integral to the function of the system, for he is the valve that allows the sounds to be heard. The electromagnets put energy into the piano strings, but that energy is only released as sound by the performer lifting his finger. There are affinities between this technique and the pipe organ. In both cases the performer acts as a
“gatekeeper” for sound. But whereas the energy stored in the windchest of a pipe organ is released by the organist hitting a key that releases a valve, in Of Dust and Sand the performer is the valve. There is no mechanism between his actions and the sound.

2.8 The Magnetic Resonator Piano

Like the Electromagnetically Prepared Piano, Andrew McPherson’s Magnetic Resonator Piano uses electromagnetic actuators to vibrate the strings of the piano. The Magnetic Resonator Piano has an actuator and amplifier for each of the 88 notes of the piano, unlike the twelve actuators and amplifiers of the Electromagnetically Prepared Piano. The Magnetic Resonator Piano uses many fewer DAC channels (16) than amplifier channels, but each amplifier is connected to signal routing hardware that allows any of the sixteen DAC channels to be connected to any of the amplifiers for a maximum of 15-voice polyphony. In terms of signal processing, the Magnetic Resonator Piano employs a feedback-based approach, using a single piezo pickup on the piano soundboard as the source. The system is designed to give the pianist access to the additional capabilities by means of a standard MIDI keyboard, or an augmented piano keyboard. McPherson has written three works for the Magnetic Resonator Piano, d’Amore, Secrets of Antikythera, and Layers Deep Below.

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65 This situation is made possible by the fact that for both the pipe organ and the Electromagnetically-Prepared Piano the energy is generated by some source other than the performer. It is not necessarily the case, however, that the energy needs to come from source external to the performer’s efforts in order for the performer to act as a valve. Instruments such as the accordion, bagpipes and harmonium store the performer’s own energy temporarily allowing him to act as gatekeeper.


67 Due to the idiosyncrasies of the signal routing system, one of the sixteen channels is reserved for no output. This phenomenon is explained in reference to another instrument in Section 3.4.
2.8.1 d’Amore

d’Amore, for viola and magnetic resonator piano, takes its inspiration from the viola d’amore. In d’Amore, the Magnetic Resonator Piano (MRP) functions much like the sympathetic strings of its namesake. Pitch-tracking of the viola triggers the resonance of corresponding strings in the MRP. The beginning of the piece demonstrates this function very clearly. The viola plays a series of arpeggiated chords. By the time the viola reaches the top note of each chord the same chord is being sustained by the MRP (Figure 2.5).

![Figure 2.5 Chord arpeggiations from Andrew McPherson’s d’Amore. The shaded triangles on the MRP staff indicate the notes being added and sustained as the viola arpeggiates its chord.](image)

The relationship of the viola to the MRP is not always as simplistic or obviously reactive as the passage that opens the piece. While the MRP’s sounds are always a response to the viola, the

68 Score excerpts used with the author’s permission.
response is not always simply an echo of the viola lines. The particular ways in which the electronics respond to the viola are composed into the piece. A separate performer or sound engineer follows along with the score selecting the appropriate patches, leaving the violist free to play without regard for the electronics.

The viola pitch tracking generates control data that are used in a number of different ways. For example, particular viola notes in a line may be highlighted, or sustained chords in the MRP may underlie entire viola passages. There are moments where the MRP swells, fades or sustains seemingly independent of the viola’s dynamics. Pitch-wise, the response of the MRP is not always one-to-one with the viola either. The MRP sometimes sustains a complete chord in response to a single viola note (Figure 2.6). One interesting effect in the piece occurs when microtones in the viola rub up against the sustained 12-tone equal tempered notes in the MRP. Another interesting effect is when a wide viola glissando triggers a chord that fills in the compass of the glissando, in a way quantizing the glissando (Figure 2.7).

Figure 2.6 Sustained chord in response to a single viola note in d’Amore.
Overall, the MRP lends a certain glow to the viola performance. Because the MRP is sounding for most of the piece (just as the viola d’amore’s sympathetic strings would), the rare moments where the MRP is silent are quite striking in their contrast to the rest of the piece. The visual effect of seeing the piano on stage with a solo string player is not unusual, but in this case the piano is sounding without a pianist. Furthermore, the sounds coming out of the piano are unexpected. In this sense, the piece likely has a different effect in live performance as opposed to hearing it on recording.

This idea of using the piano as a resonator for some other instrument is not particularly new. Luciano Berio uses the piano in just this way in his *Sequenza X* for trumpet and piano. Berio asks the trumpeter to play certain notes into the piano to excite the piano strings. At times the damper pedal is depressed allowing all notes to sound; at other times only certain notes held down silently by the pianist are allowed to resonate. The effect is something like a tuned reverb. Per Bloland also uses the piano as a resonator for a trumpet in his work *Thingvellir*. In that piece, rather than the having the trumpet play into the piano, the trumpet is miked and a loudspeaker below the piano soundboard is used to get the strings vibrating. Bloland does not call for specific notes to be depressed on the piano, instead the damper pedal is depressed throughout the piece allowing all of the trumpet notes and
their overtones to resonate, creating, as he writes in his program notes, “a sense of distance and open space.”

By using the capabilities of the MRP to create the resonances artificially, McPherson in a way frees himself of the limitations of the physics of vibrating strings—the way the piano responds to the viola is not necessarily dictated by sympathetic resonance or vibratory modes. Thus the viola’s effect on the piano is only partially causal. As previously noted, McPherson uses pitch tracking on the viola to extract control data to guide the electronics. So while the piano responses always follow the violist, the viola sound does not directly cause the piano strings to vibrate. There is a layer of processing between the viola and MRP.

Musically, the function of the MRP in d’Amore is hard to pin down, occupying a space between accompaniment and audio effect. As an accompaniment, the MRP does not really ever exert its independence to a degree that it’s completely distinct from the viola; at the same time, the MRP’s behavior seems more selective and particular than any simple audio effect. The MRP always speaks with its own voice, but part of the mystery of the piece is this uncertain relationship between the MRP and the viola.

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69 http://www.perbloland.com/?p=Thingvellir
2.8.2 Secrets of Antikythera

*Secrets of Antikythera* is a nine-movement, roughly forty-minute solo for Magnetic Resonator Piano. The piece is quite demanding of the pianist; the piano writing is dense and complex. The electronic functions in *Secrets of Antikythera* are accessed by the pianist either by an electronic keyboard controller placed above the normal keyboard, or by the piano keyboard, which for this piece is fitted with sensors to track key position. The behavior of the magnets is determined in advance, with the composer himself selecting among the preset functions in performance. While the composer selects the various presets, the pianist ultimately controls the electromagnetically generated sounds via the two keyboards described above. Thus the performer is not concerned with the macro-level functions of the instrument. This arrangement allows the pianist to focus on the already difficult task of playing the notes.

The piece begins with a movement featuring only the electromagnetically generated sounds. Notes are played without the hammer action of the piano from the auxiliary keyboard. Without the sharp attack of the hammers the sound is quite mellow and organ-like. Subsequent movements integrate the electromagnetically-actuated sounds with the normal piano sounds. In the second movement, “Conception,” a single melody line is played on the normal keyboard with its constituent notes sustained by the sostenuto pedal at the beginning of the movement (Figure 2.8). This of course gives the melody a certain resonance, but that resonance almost takes on the sound of a very faint drone. It is unclear whether those notes are being sustained artificially by the actuators, or whether it is sympathetic resonance. In either case, the effect is subtle and beautiful. After sounding on its own for a little while, the melody is accompanied by bass notes that glissando up the harmonic series from
The struck fundamental. This effect is otherworldly and yet it sounds quite natural because it is so tightly integrated with the piano both sonically and gesturally.

The fourth movement, “Creation 2,” completely explodes the sound of the piano. The movement begins with the actuators creating crescendos at the top of which the pianist strikes the same chord, creating a reverse envelope effect. The technique involves the pianist silently depressing the keys to initiate the crescendo and then striking the keys normally at the top of the crescendo. Done quickly enough, there is no perceptible break between crescendoing note and the normally articulated note. This illusion is helped by the fact that something is usually being sustained underneath (for example the D pedal tone in Figure 2.9), so the tiny gap created when the performer has to rearticulate the chord is covered by other sounds. As the movement continues, the same effect is used in ebullient contrapuntal textures that bubble and pop. The combination of crescendoing notes with normally
articulated notes is bewildering, almost as if the time domain and spectral qualities of the piano have been put in a blender and mixed up.

The audaciousness of the MRP reaches its peak in that fourth movement. For the next four movements, the MRP recedes to the background. In movement VI, the MRP is used to subtly enhance a natural acoustic effect on the piano: sympathetic resonance. Chords are silently depressed and sustained with the sostenuto pedal. These sustained notes are not articulated by the pianist. Instead, the sustained chords are revealed sympathetically by the rapid staccato notes of the normally played piano (Figure 2.10). The MRP’s sustain contextualizes the rather disjunct piano part, exposing a fairly simple voice-leading scheme at work under the more complex surface of the piano part.

Figure 2.9 Excerpt from Secrets of Antikythera, Movement IV, “Creation 2.”
The effect of the MRP in the seventh movement is quite subtle. In that movement, the magnets are used to enhance the piano’s sustain. In this case the effect is only apparent after a certain amount of time. A normally articulated note has a rather slow decay, so the effect here can only be discerned after such duration that a normally articulated note would have noticeably decayed. This leads to uncertainty on the listener’s part about whether what he is hearing are the normal acoustic effects of the piano or the actuated piano sounds. This is true even in the substantial eighth movement, which doesn’t use any MRP effects at all. The listener doesn’t know in advance that that movement is purely acoustic piano, and McPherson does not advertise that fact. The uncertainty on the listener’s part stems from the fact that the previous movements have reconditioned the listener’s expectations of the piano. Furthermore, throughout the piece McPherson uses acoustic sustaining effects, like tremolos, that force the listener to at least consider the possibility that the actuators are working even when they may not be. McPherson also manages to keep multiple registers of the piano...
simultaneously active, each with its own color, adding to the resonance and creating uncertainty over just what is making the strings vibrate, the actuators or the hammers. Unless the pianist is playing from the auxiliary keyboard the listener can’t always be sure.

Similarly to Bloland’s *Elsewhere is a Negative Mirror, Secrets of Antikythera* allows us to hear the piano in a different way. But whereas Bloland’s piece seems to amplify the timbral qualities of the piano itself, McPherson’s piece expands the notion of what a pianist can do with the piano.

### 2.9 Cage vs. Cowell

The above described instruments, techniques and pieces illustrate some of the ways that composers and performers have elicited new sounds from and explored new modes of interaction with the ubiquitous piano. Just as the performer’s relationship with the piano is changed through these methods, so too is the audience’s relationship to it. When an instrument is treated in a way that defies expectations or norms, it creates an air of mystery, or even magic, for the audience.

Cowell’s “stringpiano” and Cage’s prepared piano represent divergent (though not incompatible) ways of questioning or challenging the relationships between performer, instrument and audience. With respect to the performer’s relationship with the instrument, the Cowellian approach of reconsidering how the performer engages with the instrument is quite radical. Whereas Cage does not place any new demands on the pianist’s technique, Cowell asks the pianist to approach the instrument in an entirely new way. On the other hand, with respect to the audience’s relationship and understanding of the piano, the Cageian approach is more subversive. By having the pianist
approach the instrument in a new way, Cowell has already upset the audience’s understanding of the instrument and how it works. While the sounds in *The Banshee* may be shocking, the fact that the unusual sounds are tied to unusual ways of playing the piano makes them not altogether surprising. With the prepared piano, however, a naïve audience would have no notion that the sound should be anything other than the “normal” piano sound because our understanding of instruments derives not just from the instrument as an object, but also how a human performer engages with that object. Preparing the piano alters the instrument in ways that aren’t visible to the audience, yet the performer’s relationship to the instrument remains (at least apparently) unchanged.

Tanaka suggests that audiences create meaning in part by observing the feedback loop between performer and instrument—the performer’s effort results in some corresponding change in sound.\(^70\) Certainly with both Cage and Cowell, the effort is plainly obvious even if the resulting sounds are unfamiliar or unexpected. The sounds might make the audience curious about what’s going on in the black box of the piano, but the connection between the performer and the music—between gesture and sound—persists. The performer does *something* to make sound. In this sense the performer’s role is clear even if his actions or the resulting sounds are unfamiliar.

**2.10 Magical inaction**

The scene clouds, however, when the instrument can play itself. The previously discussed actuated pianos are capable not only of creating unusual sounds, but they have the potential to do so without

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\(^70\) Tanaka, “Musical Performance Practice on Sensor-based Instruments,” 372.
any apparent intervention on the part of the performer. This can be rather magical. In Maggi Payne’s *Holding Patterns* and Per Bloland’s “Negative Mirror” pieces, the pianist is almost a conjurer of sounds. Payne is quite explicit in her desire to keep the EBows a surprise. In my own experience as a member of the audience for Bloland’s *Negative Mirror Part II*, I couldn’t help but be not only surprised, but incredulous. Despite having read the program notes, and the fact that I could see the wires coming out of the piano, my ears still couldn’t connect what they were hearing with what my eyes were seeing and my brain knew intellectually. It wasn’t that the sounds themselves were so unusual, but that those sounds were not connected with my conception of the piano, and further, that they had no obvious origin; they did not seem tied to the pianist’s actions.

2.11 EMPP vs. MRP

Projected onto the fields of computer and electronic music, the divergent approaches to instruments and technique of Cage and Cowell mirror the divergent interests in timbre and interaction that seem to divide the field of computer music. Is the composer/researcher more concerned with creating new sounds, or in new ways of accessing and interacting with sounds? Of course, one does not preclude the other, but pushing in both directions simultaneously is challenging, and researchers’ work typically seems to be situated more in one camp than the other.
Schnell and Battier point out the case of the Ondes Martenot and Theremin which produce sound in the same way, but differ in how those sounds are accessed, i.e. the interface.\textsuperscript{71} Similarly, the Electromagnetically-Prepared Piano (EMPP) and the Magnetic Resonator Piano (MRP) produce sound the same way, but those two systems have inspired very different music. The differences in design and implementation of the two systems expose differences in how Bloland and McPherson view their respective systems.

As noted previously, the EMPP in its current form affords control over twelve piano strings, allowing coverage of the full chromatic gamut. The system is able to produce many more than twelve pitches, however, through the use of harmonics. The MRP, on the other hand, covers the entire range of the piano. This obviously increases the number of available pitches somewhat, but not by as much as it would at first appear. If the EMPP’s magnets are positioned over notes in the lower range of the piano, the instrument would still be able to produce frequencies corresponding to higher notes on the keyboard by playing them as harmonics on the lower strings.

The number of notes covered only tells part of the story in terms of the two systems’ capabilities. One of the major limiting factors for both systems is the number of DAC channels the system has. This determines the maximum polyphony of the instrument. The EMPP uses twelve DAC channels whereas the MRP uses fifteen. Viewed from this perspective the capabilities of the two systems are not as far apart as it would first appear.

Apart from some specific details of hardware implementation between the two systems, the major difference is in how the designers envision their respective systems being used. The MRP system is really an augmented piano, meaning the pianist has direct access to the new sound possibilities afforded by the electronics by means of input devices. The electronics of the EMPP, on the other hand, are controlled by computer. With the EMPP, a pianist can still play the piano in the normal way, but the pianist does not have the same access to the electronically produced sounds as with the MRP. More simply, the MRP is approached as an instrument unto itself while, as Bloland notes, the EMPP is more analogous to a loudspeaker.\textsuperscript{72}

Since the MRP can be played directly by the pianist, it makes sense from an interfacing perspective to have more notes covered. Doing so creates more of a one-to-one mapping between a physical keyboard and the corresponding pitches as sounded by the MRP. Having more notes covered potentially gives the player control over whether a particular pitch is sounded as a fundamental on one string or as a harmonic on another, or even over harmonic content or timbre of individual notes, though just how to make those distinctions becomes an interesting interfacing question.

Because there is not a dedicated DAC channel for each magnet with the MRP, additional hardware and software are needed to route the audio to the appropriate magnet. By contrast, these complications are avoided in the EMPP because in the EMPP each magnet essentially functions as a single speaker in a multichannel audio system. The composer is responsible for ensuring that the correct sounds get to the appropriate string either through software design or by creating specific audio files.

\textsuperscript{72} Bloland, “The Electromagnettically-Prepared Piano and Its Compositional Implications.”
Both electromagnetic piano systems allow for very fine-grained, continuous control over the harmonic content of the sounds that are created. In this regard, one of the significant limiting factors of the MRP system is the human performer. The timbre or harmonic space for even a single note is potentially very high-dimensional. Because the MRP is intended as a real-time instrument, the high dimensionality of the timbre space presents challenges for the performer as well as the composer/interface designer.

Broadly speaking, the EMPP system would seem to support a timbre-focused compositional approach better than the MRP, whereas the MRP system supports interactivity better than the EMPP, and indeed that is borne out in the music.
3 The EMvibe

3.1 Actuated acoustic instruments

The Electromagnetically-Prepared Piano and the Magnetic Resonator Piano are both examples of actuated acoustic instruments. Actuated acoustic instruments represent a subcategory of actuated instruments, which Berdahl, Overholt and Hamilton define as “those [instruments] which produce sound via vibrating element(s) that are co-manipulated by humans and electromechanical systems.” While their definition is sufficiently broad to encompass several vastly different performance systems described in their article, the key point is the notion of co-manipulation by human performers—and that human performers are considered in the equation at all. This distinguishes actuated instruments from robotic instruments.

Andrew McPherson suggests that for actuated acoustic instruments, the actuation technologies should afford new sounds and capabilities that exist alongside the instrument’s more traditional sounds, and further, that they do so without the use of loudspeakers. These instruments aren’t simply set into vibration and left to decay on their own, but rather they are actuated constantly over the course of a given note. Getting sounds on these instruments that are not available by traditional

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75 Their article describes both of the previously discussed electromagnetic piano systems, an electronic violin whose body is actuated by a tactile sound transducer, an electric guitar with electromagnetic actuators, the use of multiple haptic force-feedback devices to play non-pitched percussion instruments remotely, and a drum pad that hits back when struck.
means necessitates audio rate (as opposed to control rate) actuation. This near-constant audio rate excitation is what affords these instruments expressive and timbral possibilities beyond their un-actuated counterparts.

Actuated acoustic instruments distinguish themselves very well when they do things quite unlike their un-actuated variants. If one is interested in obtaining new sounds from acoustic instruments by means of “audio rate” actuation, the most obvious candidates for such alterations would be those instruments whose sound is not ordinarily produced by sustained excitation. Actuation allows instruments that, like the piano, are ordinarily excited with an impulse to be controlled more continuously, giving the instrument new capabilities while preserving the old. It is rather more difficult to imagine how actuation could be used to give new capabilities to an instrument like the trombone, for example, because the trombone already requires constant excitation in order to sound. What resonant bodies would the actuators work on and how would the original capabilities be maintained?

Dan Overholt’s Overtone Fiddle is an interesting case of an instrument (the violin) that is normally sounded through constant excitation (i.e. bowing), but whose capabilities are augmented via actuation. With the Overtone Fiddle it is not the strings that are actuated, but rather the instrument body, which for the violin functions as an acoustic resonator. String vibrations are sensed by magnetic pickups, and that sound is processed and played back through a tactile sound transducer.

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76 Andrew McPherson made this insightful observation in response to a question about differences between robotic and actuated instruments during the Workshop on Actuated Acoustic Instruments at NIME 2012, Ann Arbor, MI.
embedded in the instrument body. The direct physical coupling of strings and instrument body that is normally made by the bridge and sound post is severed in the Overtone Fiddle. The string-body connection is instead mediated by a computer, allowing the user to do things like emulate different instrument bodies or sympathetic strings, for example, thereby changing the apparent acoustic qualities of the instrument.

The Overtone Fiddle is a bit of an outlier in the field of actuated acoustic instruments. The base instruments for the majority of the viable actuated acoustic instrument systems exhibit the quality describe above, that once they are excited through an initial impulse, the performer has little to no subsequent control of the sound other than to stop it. There are the two previously described electromagnetic piano systems, systems for electric guitar,78 79 drums,80 81 Fender Rhodes,82 and the vibraphone.83 While one may quibble with just how “acoustic” the Fender Rhodes and electric guitar are, they are mentioned here because their sound is produced via mechanical oscillations in the instruments themselves, as opposed to the sound being generated electronically. For all of these instruments, the actuation provides sustain, longer attack envelopes and spectral evolution—things the base instruments are incapable of.

78 Nic Collins’s backwards guitar: http://www.nicolascollins.com/texts/BackwardsElectricGuitar.pdf
80 Roberto Mario Aimi, “New Expressive Percussion Instruments” (Masters, Massachusetts Institute of Technology, 2002).
83 Britt, Snyder, and McPherson, “The EMvibe: An Electromagnetically Actuated Vibraphone.”
3.2 Overview of the EMvibe

The vibraphone is a keyboard percussion instrument consisting of aluminum tone bars suspended over metal tubes that act as resonators. Its name is inspired by the vibrato effect made possible by sets of fans driven by an electric motor that open and close the resonators, a feature not found on other keyboard percussion instruments. The effectiveness of the vibrato is due in part to the relatively long decay time of the instrument. The long decay time also necessitated the addition of a damper pedal, another feature not found on most other keyboard percussion instruments. This long decay time also makes certain extended playing techniques, such as bowing, playing harmonics and certain preparations particularly effective on the vibraphone, because the sound rings long enough for those effects to be heard.

The EMvibe augments the acoustic vibraphone with electromagnetic actuators. Controlled by a computer, these actuators allow the electromagnets to “bow” the vibraphone bars, affording the potential for infinite sustain of up to seven notes simultaneously, as well as control over the instrument’s overtones. All of the sound emanates from the instrument itself, without the use of loudspeakers, and the added hardware does not interfere with the normal playing techniques of the instrument.

The basic technique for electromagnetically actuating the vibraphone bar is as follows: A small permanent magnet is attached to the vibraphone bar, and the electromagnetic actuator is positioned near, but not touching the permanent magnet. The electromagnet is driven by an audio signal
creating a magnetic field that pushes and pulls the permanent magnet, and thus the bar. If this pushing and pulling happens at one of the vibraphone bar’s resonant frequencies, the bar will sound.

### 3.3 Vibraphone Mechanics and Acoustics

Unlike strings, which theoretically support integer multiples of their fundamental frequencies, vibraphone bars support relatively fewer harmonics. Vibraphone bars have arches cut in the underside to emphasize the fundamental frequency and tune the most prominent overtone, making it more harmonic. The first overtone is tuned to approximately four times the fundamental frequency, or double octave. The frequencies of higher partials do not maintain a consistent relationship to the fundamental, and that relationship is frequency dependent and non-harmonic. Overtones are also more prominent in the lower range of the instrument than in the upper range. In the lower range of the instrument the second overtone is close to ten times the fundamental frequency (Figure 3.1). Sounding at approximately four- and ten-times the fundamental frequency, the vibraphone’s most prominent overtones are even harmonics.

![Figure 3.1 The most prominent partials of F3 on a vibraphone.](image)

Vibraphone bars are suspended over the instrument’s resonators by means of a cord running through holes drilled through the width of these bars. The holes are positioned at nodal points. Because
vibraphone bars are aluminum, the electromagnetic actuators cannot act directly on the bars. To couple the bars and the actuators we use small neodymium magnets affixed to the undersides of the bars. The permanent magnet is what the actuator pushes and pulls to move the bar. Performance is therefore tied to the magnets’ placement. These permanent magnets and the actuators should be positioned at a point of maximum displacement—a spot where the bars travel the most. For a variety of reasons, the ends of the bars were chosen for placing the magnets.

According to Rossing, for shaped bars such as those of the vibraphone, the point of maximum displacement is the center of the bar when the bar is struck. However, displacement actually depends on the bar’s mode of vibration. Under normal playing conditions the performer can emphasize (or de-emphasize) different modes to an extent by changing the striking position, but it is not normally practical or possible to isolate individual modes. However, by using electromagnetic actuators, we can induce specific vibratory modes. With the EMvibe we are primarily concerned with the first two or three modes, and for both of these modes, the ends of the bars provide if not the maximum displacement for a given mode, at least some displacement. This is not the case for the center of the bar, which is actually a node for the second mode of vibration. So even if it were practical to place the magnets and actuators at the center of the bar, we would not be able to get the first overtone (second vibratory mode) to sound.

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3.4 Physical design

The EMvibe consists of thirty-seven electromagnetic actuators, one for each bar on the standard three-octave vibraphone. Each actuator has a dedicated amplifier. Audio is synthesized by a computer and delivered to the amplifiers via an eight-channel DAC. Any of seven DAC channels
can be connected to any of the coils using a series of shift registers and multiplexers in conjunction with a microcontroller to route the signals.\textsuperscript{85}

The signal routing works as follows. A multiplexer receiving signals from all DAC channels is at the input of each amplifier. The multiplexer allows only one of the signals to be connected to the amplifier at a given time. The input channel is selected by a shift register connected to the multiplexer. The shift registers are 8-bit, and each multiplexer requires three bits to select among the eight DAC channels, so there is one shift register for every two amplifier channels.\textsuperscript{86} A Teensy 2.0 microcontroller\textsuperscript{87} serves as a go-between between the voice management software on the laptop and the signal routing hardware. Fed a series of bytes from the voice management software running on the laptop, the microcontroller then sets the shift registers. It is not possible for a multiplexer to have no input selected, so one of the idiosyncrasies of this set up is that the each amplifier is always connected to some DAC channel. In practice this means that one DAC channel must be reserved as “no output.” Thus with eight DAC channels we can have seven-voice polyphony, the eighth channel being “no output.”

Amplifiers and signal routing hardware for seven channels are contained on a single circuit board. These circuit boards, along with the actuators, are mounted on aluminum brackets clamped to the frame. In addition to holding the actuators in position under the bars, the brackets serve as heatsinks

\textsuperscript{85} A multiplexer is an electronic component that takes several input signals (in this case eight) and allows one of those signals to be passed on. In our usage, the shift register allows serial data to control the multiplexers. Data are expressed by the shift registers as high or low voltages. These data bits represent binary numbers that select the multiplexer input to be passed on. The shift registers are wired in series and data is passed down the line until a “latch” signal writes the data to the shift register’s output pins, setting all of the multiplexers at once.

\textsuperscript{86} In our system we actually use an odd number of amplifier channels on each circuit board, so one shift register per board controls only one multiplexer.

\textsuperscript{87} Teensy 2.0: http://www.pjrc.com/store/teensy.html; purchased February 2012.
for the actuators. Individual circuit boards are daisy-chained with the first board in the chain connected to an external enclosure containing power supplies, audio connections from the audio interface, and the microcontroller for signal routing. This power box is connected to the first amplifier board in the chain using DB25 connectors (Figure 3.3), while the remaining boards are chained using ribbon cables (Figure 3.4). There are three circuit boards on each side of the instrument. The amplifier channels on the natural (performer) side of the instrument are all used (and one has to be borrowed from the other side). On the accidental (audience) side of the instrument, only five of the seven amplifier channels are used.\footnote{This is slightly wasteful, but it simplified the manufacturing process because all of the boards could be manufactured the same way.} Between the connection of the accidental and natural sides of the instrument is a small circuit board that buffers the control signals for signal routing. Without this buffering the signal routing is unreliable.
Figure 3.3 Photo showing the external enclosure for the power supplies, the first circuit board in the chain and five actuators.
3.4.1 Initial Setup

In addition to mounting the hardware on the instrument, initial setup requires that the tuning of the synthesized excitation tones music be matched with the resonant frequencies of the vibraphone bars. This tuning process is undertaken for the fundamentals of each bar and the first harmonics for most of the instrument’s range. This is done by ear, adjusting the frequency of the oscillator by hand and judging when the maximum response is achieved. The frequency is associated with the note’s MIDI number, and the pair of numbers is written to a text file on the laptop that the performance
software then references. This procedure is undertaken once per installation and takes about a half hour.

### 3.5 Amplifier design

Early on in development, we tested actuating the vibraphone with a square wave under the assumption that, for a given output level on the amplifier, a square wave would contain the most possible energy and would potentially give us greater volume than a sine wave. Indeed the square wave did provide a louder tone. However, the fact that the square wave provided a louder tone is somewhat surprising given the acoustic properties of the vibraphone. While it is true that the square wave has greater energy than a sine wave for a given voltage swing, it is also the case that that energy is in odd integer multiples of the fundamental frequency. The even harmonics of the vibraphone should not be affected by a square wave. This was also the case; the fundamental tone was louder and the harmonics remained unaffected. Because the vibraphone bars support so few vibratory modes, they effectively filter out frequencies other than those that are supported. This early discovery that square waves could be used to drive the bars with no negative effect on sound quality was an important consideration in our amplifier design.

Also in our early testing, we discovered that we needed considerable power to generate what we deemed to be a sufficiently loud tone as to be musically useful. We had been successful using high fidelity audio power amplifiers for our initial tests, but it seemed cost-prohibitive and impractical to use more than a couple power amplifiers. Andrew McPherson devised a quite simple and cheap
amplification system to suit our needs. The system leverages the fact that we can use square waves to achieve sinusoidal responses. It also takes advantage of the fact that, because our actuators are acting on permanent magnets, we can both attract and repel the magnet by changing the direction of current flow through the electromagnet. 

McPherson’s amplifier design essentially switches between positive and negative voltage sources to generate a signal of positive- and negative-going pulses. When played through the electromagnetic coil, this signal will push or pull the permanent magnet depending on the polarity of the signal. This amplifier design has a couple of significant advantages. First, it is inexpensive. Each amplifier channel uses only a handful of components and multiple amplifier channels can share the same power supplies (i.e. voltage sources). The second big advantage is that this amplifier design requires no heatsinking. Thus the amplifiers can be very compact since we do not have to account for bulky heatsinks when thinking about installation. This allows for greater flexibility in positioning them on the instrument.

However there are also disadvantages to this design simplicity, particularly in terms the kinds of signals the amplifiers are able to reproduce, and the requirements of the input signal to ensure safe operation. We use two power supplies in our system, one +24VDC and the other -24VDC. These should not both be connected to the output at the same time. This system only allows for three output states: +24VDC, -24VDC, and no output, and can thus produce a positive voltage pulse or a negative voltage pulse. A positive-going input signal will trigger a positive pulse, for as long as the

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89 This is in contrast to the effect of an electromagnet on ferrous metal, which is always attractive regardless of the direction of current flow.
input signal remains positive and similarly for negative-going input signals (Figure 3.5). The amplitude of the system is determined by the width of these pulses.

![Figure 3.5](image) The waveform used to drive the EMvibe actuators. Note the dead bands between the positive- and negative-going portions of the waveform.

Each amplifier channel uses two power MOSFETs to switch the voltages, one for positive and one for negative (Figure 3.6). If both voltage sources are connected simultaneously the resulting condition, called shoot-through, can damage the amplifier (with smelly and even fiery results!). To prevent this from happening, we need to ensure that the input signal includes a dead band between changes in signal polarity, that is, a short period of time during which the signal is neither positive nor negative (Figure 3.5).

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90 The amplifier essentially hard clips the input signal.
Figure 3.6 Block diagram for a single EMvibe amplifier channel. The power MOSFETS are labeled Q3 and Q4.

3.6 Signal processing

Given its limitations, our amplifier cannot reproduce arbitrary waveforms. As noted previously, the high-frequency components resulting from these pulse waves are filtered out by the vibraphone bars. The bars simply do not support these vibratory modes. We prevent shoot-through by ensuring that our input signals are generated with the required dead band. Still, we are apparently limited to simple waveforms and, owing to the vibraphone’s acoustics, only one partial at a time. We cannot generate a continuous signal that includes the fundamental and harmonic(s).
To obtain more complex responses we use multiple oscillators, one per partial, tuned to the desired frequencies. We switch between the multiple oscillators 20–30 times per second. In this way we are able to generate a more complex bar response without a complex waveform. Just as we control the amplitude by varying the pulse width, we can control the spectrum by varying the proportion of time each oscillator is sounding.

By switching between multiple oscillators, as opposed to switching the frequency of a single oscillator, we ensure that the oscillators and vibraphone bar remain in phase. If we were to change the frequency of a single oscillator from the fundamental to the first harmonic and back, for example, it is possible that the phases of the oscillator and bar might not match when the oscillator switches back to the fundamental. Phase is significant because, particularly for the fundamental, it takes some time for the bars to reach maximum amplitude. If we were to ignore phase we would potentially limit our amplitude because there is no way to guarantee that the oscillator will be in phase with the vibrating bar when switching between partials. Figure 3.7 shows the switching waveform and its constituent components.
Figure 3.7 Switching between oscillators to maintain phase: a) shows the switching waveform, b) and c) show the two individual oscillators on their own. Note that when the switching waveform (a) goes back to the fundamental it is still in phase with the continuous fundamental waveform (c).

3.7 Composing the EMvibe

In Chapter 1 we considered instruments on the basis of their inputs and outputs, and in terms of human interaction with those inputs and outputs. The EMvibe, and indeed most other electronic instruments, involves some circuitry or software to connect inputs and outputs because they are not directly coupled, as they are in most acoustic instruments. This means that the connection of gesture to sound must be made by the composer or instrument designer. The term “composed instrument,” used to describe these situations, implies a connection between composition and instrument design. While the EMvibe affords new sound possibilities for the vibraphone, the hardware itself does not suggest how those capabilities might be used or accessed by a performer or composer. “Composing

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91 Schnell and Battier, “Introducing Composed Instruments, Technical and Musicological Implications.”
the EMvibe” then entails the selection of input devices (i.e. interfacing) and, in software, the mapping of control data from the selected input devices to the output sound. These two tasks are interdependent; each influences the other.

### 3.7.1 Software

Use of the EMvibe requires a laptop. Software for the instrument exists on two different levels: a functional level and a musical layer. The functional software layer controls the system’s most basic functions: synthesis, voice management and communication with signal routing hardware. The audio must be synthesized to the requirements outlined in sections 3.5 and 3.6 above, namely bipolar pulse waves, one oscillator per partial and switching between the two according to the desired mix of partials. The audio signals are synthesized with the dead bands in each oscillator as well as an additional dead band when switching between oscillators (because there’s no easy way to know the state of the oscillators when switching back and forth).

The voice management software and the communication with the signal routing hardware work hand in hand. The voice management software allocates voices on a first in first out (FIFO) basis until all available DAC channels have been assigned. When a change in signal routing is required, data bytes are sent as MIDI Control Change messages to a Teensy 2.0 microcontroller configured to appear as a USB MIDI device.
Additionally, this software layer supports the basic proto-musical functions afforded by the hardware including: the starting and stopping of notes, volume control, and controlling the harmonic mix. These functions are controlled by standard MIDI messages, meaning that any standard MIDI controller or software can be used to control the basic functions, so long as the particular MIDI device supports the appropriate message types. The establishment of MIDI as a protocol for communicating with the hardware essentially turned this functional software layer into a black box. MIDI seemed like a good choice because of its ubiquity, and the protocol’s speed, bit depth and bandwidth are adequate for our purposes.

The control parameters of the EMvibe are spectrum, amplitude, and frequency. The spectrum, or harmonic content, refers to the relative amplitudes of the fundamental and overtone(s). While spectrum refers to the relative amplitudes of individual partials, amplitude controls the overall level. The MIDI layer uses Note On/Off messages to start and stop notes, and Control Change messages to set amplitude and spectrum globally. Additionally, both amplitude and spectrum can be set per note, using Polyphonic Aftertouch for amplitude and Channel Aftertouch for spectrum.

The decision to establish a protocol at all (MIDI or otherwise) was significant. Being freed from thinking about the basic workings of the instrument allowed me to begin to think about the instrument more musically and greatly simplified the programming on the musical layer.

92 We currently use only one overtone.
3.7.2 Interfacing

How does the performer and/or composer access and control the extended capabilities of the EMvibe? What is the interface? The short answer is that there isn’t one. The EMvibe was not designed with a single interface in mind. Indeed, the thought is that different pieces will demand different interfacing and mapping strategies and the exploration of various modes of interaction is motivating continued work on the instrument. There are two broad categories of use for the EMvibe, each placing the performer in a different relationship to the instrument, and thus demanding different interfacing strategies. The EMvibe may be used as a new sound source, or as an augmented instrument.

While the EMvibe sounds like an acoustic instrument (indeed all of the sound is radiated acoustically), it is also an electronic instrument because those capabilities which the electronics afford are controlled by a computer. The question of how to control those features is a big one, and one of the more interesting aspects of this project.

Taken as a new sound source, where the vibraphone player (if there is a human player on the instrument at all) does not have direct control over the extended capabilities of the instrument, interfacing with the EMvibe is fairly straightforward. The EMvibe software can be configured to respond to virtually any MIDI device using the messages described previously.

As a sound source controlled by some external physical controller, the EMvibe presents no unique challenges to the user. As with any novel interface or synthesis technique, the user still has to come
up with a mapping strategy. The question of how to connect controller outputs to the EMvibe’s inputs may have different answers depending on the musical context.

As an augmented instrument, where the player gains access to the extended capabilities of the instrument, the EMvibe presents significant challenges. Augmenting vibraphone technique to control the EMvibe is challenging because: 1) the vibraphone player actively uses three of his four limbs (and the other is needed for balance) and 2) the performer cannot maintain constant physical contact with the instrument without adversely affecting the instrument’s ability to vibrate.

The use of pitch tracking on the vibraphone avoids these complications, allowing the vibraphonist to access the EMvibe’s new capabilities without altering his technique. It has proven to be a very successful, natural means of controlling the instrument. The EMvibe’s pitch tracker is, for the most part, used to trigger note-level responses, the specific characteristics of which (e.g. volume, duration, spectrum) are determined in advance and recalled as presets.

The current pitch tracker uses a bank of narrow bandpass filters, with one filter for each bar. Incoming audio is decomposed by the filter bank. If the response of any of the filters is above a certain threshold then a “note on” event is triggered. The current pitch tracking system is not the most technically advanced, but it is robust and reliable. We do not currently extract amplitude data for the incoming audio, though that is certainly a possibility. The pitch tracking software sends its “note on” messages to the voice management software that then deals with voice allocation, ignoring incoming messages if no voices are available. “Note off” messages are not generated by the pitch
tracking software, but rather by some other software component. In typical usage the durations of
the actuated notes are set to some pre-determined length.\(^93\)

When the vibraphone is played acoustically, there is a correlation between amplitude/volume and
note duration. Louder notes have longer decay times than shorter notes.\(^94\) Also, once the vibraphone
bar is excited—by mallet, bow, or electromagnetic actuation—it takes a certain amount of time for it
to ring down so long as the damper mechanism is disengaged. Our pitch tracking software maintains
this aspect to an extent by virtue of the fact that no notes are triggered for incoming signals that do
not exceed a minimum threshold.

The above discussion assumes that pitch tracking is being used on the vibraphone itself and that
incoming pitch data are mapped one-to-one to the same notes. However, there are many possible
ways to use this incoming data. The most obvious is of course to have the vibraphone itself trigger
the notes, but the system works equally well using incoming audio from another instrument or
sound source to trigger notes on the vibraphone. Used this way the EMvibe can become a sort of
artificial resonance for some other sound source.

Incoming pitch data can also be remapped in infinitely many ways. A simple, but rather interesting,
remapping is having the EMvibe respond with the note an octave above the pitch that was detected.
This technique is discussed in more detail in Section 3.9.1 below. Other remappings are possible by
adding code between the portion of the software that receives note data from the pitch tracker and

\(^93\) If the predetermined duration of the note is short, the effect of the actuation can be quite subtle because struck notes
have a certain ring time naturally. With longer note durations, however, the effect of the actuation is more obvious.
\(^94\) Register plays a role here too—lower notes (i.e. longer bars) have longer decay times.
the part that generates the notes, or by preprocessing the incoming audio. For example, one could use ring modulation or some other effect on the incoming audio and do the pitch tracking on the resulting audio. With ring modulation, the possibility exists for a single input frequency to generate multiple notes within the range of the vibraphone depending on the frequency and wave shape of the modulator. In this case, some kind of chord may result from a single sounding note, a one-to-several mapping of incoming events. An incoming “note on” event could also trigger a sequence of notes, or the incoming control data can be delayed in time. The more complex these mappings or remappings become, the more the results begin to take on musical significance in their own right, and the more instrument design becomes an act of composition.

We are only in the beginning phases of this part of our research, but we suspect that camera tracking holds a lot of promise as a means to control the EMvibe. Odowichuk et al have explored such a strategy using Microsoft Kinect\(^5\) to track the performer’s gestures. Additionally, reacTIVision and the TUIO\(^6\) protocol could potentially be used to control the EMvibe through the tracking of objects on the top of the instrument. Sensor-based approaches, where the sensors are placed on the performer, may also prove interesting for certain musical contexts.

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3.8 Sonic results and musical possibilities

The sound of the EMvibe might best be described as ethereal. The sound is pure and the attacks are legato even at their fastest. The electromagnetic actuation is quite effective when the damper pedal is depressed, but the response is extremely weak with the damper bar engaged.

The amplitude response is much stronger for the fundamental than for the overtones, although overtones respond more rapidly than do fundamentals. The vibraphone’s resonators, the tubes suspended below the instrument, play a role here. These tubes are capped at one end, and they are tuned to the fundamental frequency of the bar above. Because the tubes are closed at one end, they only support the fundamental and odd harmonics. The vibraphone has no odd harmonics. So while the bar’s fundamental gets a boost from the resonator, the resonator has no effect on the overtones.

In the lower range of the instrument we were able to isolate the first two harmonics, but the availability of the harmonics diminishes in the upper range to the point that they are not available in the highest range of the instrument. This diminished high frequency performance is likely due to a combination of the acoustics of the instrument and attenuation in the electromagnets. The attenuation in the electromagnets may be caused by coil inductance as well as potential losses in the core at higher frequencies.

The EMvibe affords playing legato passages much more rapidly than is possible with a bow. It is also possible to sustain chords of up to seven notes. Crossfading between harmonics works well, and different effects can be achieved by crossfading at different rates. An interesting forte-piano-
crescendo effect can be achieved when an electromagnetically actuated bar is struck with a mallet. This technique is not reliable though, as it depends on the phase of the bar at the moment the mallet strikes.

We expected the sound of the EMvibe to be somewhat similar to that of bowed vibraphone, and indeed there are similarities. As with bowing, it is possible to generate very smooth attacks. Unlike bowed vibraphone, however, the EMvibe lacks some of the high frequency content characteristic of bowed vibraphone (Figure 3.8). Surprisingly, when passages are played on the EMvibe the sound is quite reminiscent of a flute stop on a pipe organ.

![Figure 3.8 Spectra for vibraphone note A3 sounded four different ways.](image)

In gaining the potential for sustain, the EMvibe becomes an instrument that can play itself, possibly without direct input from the player. The fact that the instrument can sound on its own opens up performance techniques that are not possible on the acoustic vibraphone. For example, the normal
notion of how effort is applied in performance can be reversed so that rather than the performer putting energy into the instrument to make sound, the performer uses his energy to stop the instrument sounding. Or he may take a negative action, un-dampening a sounding bar, allowing the instrument to sound. Not only does this create sounds that are not possible on an acoustic vibraphone, but it also creates ways of engaging with the instrument that were previously unimaginable.

Depending on how the software is programmed, the EMvibe can respond to a performer’s input, or create sound with no input from the performer. In the former case, the electronic aspects of the instrument may respond to the performer’s input in a way that supports what the performer is doing musically. On the other hand, the instrument could respond in a way that creates a sort of creative friction, a response that the performer then has to deal with musically. The instrument in both of these situations becomes a collaborator with the performer, almost like another performer.

3.9 EMvibe pieces

The EMvibe has been used in two pieces to date: *Ctenophora*, composed by the author, was recorded by Sideband at Princeton University in June 2012 and *Are you still busy being mad at me?* is a dance piece that choreographed by Tommy DeFrantz that premiered at Duke University in March 2013. These two pieces use the instrument in radically different ways. *Ctenophora* uses the EMvibe as an instrument, while *Are you still busy being mad at me?* uses it as a new sound source.
3.9.1 Ctenophora

In *Ctenophora*, for EMvibe and three laptop performers, each of the piece’s five sections represents a different way of thinking about and interacting with the EMvibe. The opening section uses the EMvibe to fade drones in and out independent of the performer’s actions. This sequence of drones was composed in advance, and it is played as a MIDI sequence from the laptop. The second section of the piece uses pitch tracking to trigger long (9 second) notes in response to those same notes being played on the vibraphone. Once clusters of notes are excited and sustained by the EMvibe, the vibrating bars are touched lightly with small triangle beaters, allowing them to vibrate against the vibrating bars as a sort of temporary preparation.

The laptop performers use the tethers of Mad Catz Real World Golf’s Gametrak controllers to control a phase vocoder instrument that allows samples of bowed vibraphone to be manipulated. The tether performers fade their sounds in part way through the first section and try to mimic the activity level of the EMvibe in the second section.

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97 The tether instrument was made by Dan Trueman and adapted by the author for this piece.
The third section begins with a loud minor second played in the low register of the vibraphone. Those notes are then sustained by the EMvibe throughout the rest of this section. Interestingly, because of the range of those two pitches and the fact that the response of the vibraphone to the actuation is sinusoidal, the sonic result is not a sustained minor second, but rather a single tone beating at 11Hz. The EMvibe acts as a subtle sustainer for other notes played in this section. In this section, the tethers use an alternate tuning system and fade their notes in and out in response to the EMvibe. The equal tempered vibraphone pitches rub up against the alternatively tuned pitches in the tether parts, creating the illusion of a microtonal vibraphone.

The fourth section uses a similar scheme to the previous section in terms of how the EMvibe is used: several notes are sustained throughout the section while pitch tracking is used to control the sustain.
of other notes. Unlike the previous section, however, in this section the EMvibist interacts with the sustaining notes. The performer creates an ostinato by sequentially muting and un-muting the sustaining notes, creating an almost organ-like sound. The action here inverts the normal energy-input of the vibraphone: rather than creating sound by striking the notes, the notes are allowed to sound by lifting the mallet off of the bars. The ostinato notes are articulated by the EMvibe only, without a mallet strike, creating an entirely different attack envelope from the struck notes.

The final section of the piece is for EMvibe alone. It again uses pitch tracking to control how the EMvibe responds, but instead of triggering the same pitch that was tracked, the triggered note is an octave higher than that detected by the pitch tracker. The result of this remapping is an octave doubling. However, because the higher octave note is not initiated with a mallet strike the two pitches fuse in an interesting way. The result sounds more like a timbre change than an octave doubling. This has a rather interesting effect on the vibraphone because the vibraphone does not exhibit an overtone at the single octave, so with this effect the vibraphone takes on a different character, somewhat similar to steel pan. In terms of its implementation in software, this effect is not quite as straightforward as it might first appear. In order to double the notes of the highest octave of the vibraphone an octave higher, I have to use the two-octave harmonic of the middle octave of the vibraphone (Figure 3.10).
3.9.2 Are you still busy being mad at me?

The EMvibe was used as part of the sound design for Tommy DeFrantz’s dance piece *Are you still busy being mad at me?* While the instrument appears on stage, there is no vibraphonist for this work (Figure 3.11). Instead, the speech sounds of the three dancers are played through the EMvibe. In the performance each of the dancers tells a story which, in addition to being heard by the audience, is filtered through the EMvibe. Each performer has a unique EMvibe sound associated with them. Preparations on the vibraphone are used for two performers, while the unprepared sound of the instrument is used for a third performer. Bead chains laid across the instrument create a bright, metallic buzz, but also dampen notes more quickly, while sheets of aluminum foil laid over the instrument create a nasal, kazoo-like buzz.

The speech can be followed more or less closely by the vibraphone by adjusting there main variables: the threshold above which the EMvibe is triggered, the input gain on the filters that preprocess the audio, and the length of notes that are triggered by the pitch tracking software. All three of these variables, plus the overall gain of the EMvibe and the EMvibe’s spectral content, were adjusted in real time by the author during the performance.
Figure 3.11 The EMvibe in Tommy DeFrantz's *Are you still busy being mad at me?*, March 2013
4 Epilogue

When the composer has figured into the previous discussions, it has been from the viewpoint of an audience listening to, or a performer playing a composer’s completed work and the unusual ways composers have treated certain instruments. Let us now consider what might motivate a composer to treat perfectly good instruments in unusual ways. Why add complicated technologies to already robust and highly evolved instruments? What does the composer gain by so doing?

While it’s true that the composer gains new sounds and new capabilities, the desire for new sounds hardly seems sufficient to justify the effort involved in creating some of the previously discussed actuated instruments. If new sounds are what the composer or instrument maker are after, there are surely easier ways than putting 88 electromagnetic actuators into a grand piano.

We might instead ask why might a composer be interested in new sounds at all? Certainly there are sound fetishists. But for myself, and I’d imagine other composers, new sounds and technologies are useful for breaking habits and uncovering new ideas. In his article “Music as an Action Sport,” Steven Mackey writes, “I refuse to accept any idea that my brain can think of” and goes on to describe an elaborate precompositional scheme that “was aimed at helping me think of something I otherwise wouldn’t.” 98 While Mackey was not speaking of new technologies per se, he articulates a similar interest in creating and confronting new situations as a means of fostering creativity.

Changing the way an instrument works or is used is useful for reinvigorating the compositional

process by changing the terms of engagement, forcing the composer to deal with something unfamiliar. It changes the composer’s mind-set.

Composers and instrument makers doing the sort of work discussed here deliberately seek to disrupt the sense of “flow” discussed in Chapter 1, purposely rendering the instrument “present at hand” by changing its properties in some way. Dreyfus uses the term “breakdown” to describe this devolution.99 While breakdowns might be detrimental to performance, they can inspire creativity by forcing the composer or instrument designer to look at an instrument afresh. Suzanne Bødker observes that breakdowns are “openings for learning.”100 Breakdowns can expose new solutions to the general problem of writing music.

When a composer alters an instrument’s behavior or the way it is interfaced, he is potentially venturing into uncharted waters. He may have an idea how the instrument will sound or respond, but that idea might not be completely accurate. Without precedents to draw upon he’s really just guessing. If we think of altering instruments generally as imposing a sort of breakdown, even these breakdowns can have breakdowns if/when results defy expectations.

The EMvibe certainly didn’t sound like I’d imagined. I guessed that it would sound like bowed vibraphone, but there were a couple of ways in which that guess turned out to be wrong. While notes can be sustained for a fairly long time with a bow—particularly as compared with normally

struck notes—duration is still ultimately limited by the length of the bow (bow changes don’t work very well with the vibraphone). Having a note sustain indefinitely and unwavering, as the EMvibe can do, turns out to be very different from bowed vibraphone. Removing the characteristic envelopes of the vibraphone sound changes its character. In addition, there are aspects of the timbre of bowed vibraphone that are absent with the EMvibe: the noise of the stick-slip of hair against the bar and the other vibratory modes induced by scraping the ends of the bars. I’m not sure any amount of reasoning about how the EMvibe might sound would have produced an accurate mental image of its actual sound. Interestingly, I learned quite a bit about the sound of bowed vibes by noticing and thinking about what was missing with the EMvibe.

By playing around with the new sounds or capabilities afforded by an altered instrument, the composer can begin to imagine a context for those sounds. In fact, if the abilities afforded by the instrument are new, the composer has to play around and explore with them in order to discover what’s physically possible, let alone musically interesting.

Klemmer, Hartmann and Takayama distinguish pragmatic action from epistemic action. Pragmatic action, they write, involves “manipulating artifacts to accomplish a task” whereas epistemic action entails “manipulating artifacts to better understand the task’s context.”¹⁰¹ The traditional piano-in-the-composer’s-studio is used pragmatically. In this case the piano is not inspiring the music, but rather giving voice to the composer’s musical ideas as he shapes them; the composer is acting through the instrument, not on it. It’s harder to imagine using the Magnetic Resonator Piano in this

way, as a sort of general-purpose compositional tool. Somehow its relative unfamiliarity makes it seem too specific.

Of course all instruments are specific, each has its own characteristics that enable us to distinguish among different instruments. But familiarity allows the listener or performer or composer to “listen past the instrument in a way that’s hardly listening at all,” to riff off of David Sudnow’s quote from the first chapter. The familiar instrument can become invisible. That is less possible with unfamiliar instruments. Unfamiliar instruments seem more specific and particular than familiar ones.

Added to this notion of relative familiarity is the fact that the behavior of the Electromagnetically Prepared Piano, for example, has to be configured in advance, or the prepared piano prepared ahead of time. These are compositional acts with real musical ramifications. This ability to configure the instrument—to compose the instrument—creates a context that the composer may then discover through epistemic action, through playing.

Trueman recognizes the complexities and interdependence of instrument design and composition in his discussion of “virtualizing” the violin. He writes: “although we don’t actually alter the physical interface, we can change the way it responds, forcing the player to adapt. In this way, instrument design, composition, and performance combine into a single activity.” With the virtual violin project Trueman was discussing, as with the EMvibe, the same person assumes all of those roles (or the one complicated role): the same person is the instrument builder, composer and performer. But

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102 Of course it could be argued that any time a composer decides on instruments that’s a compositional act. True, but the axiom of familiarity still applies: the more unfamiliar an instrument, the more specific or particular it seems.

even if the composer/instrument builder is not the “end user” (i.e. performer) of the technology, as with the Electromagnetically-Prepared Piano and the Magnetic Resonator Piano, the process of composition necessitates playing with the instrument. And changing the way the instrument responds forces the composer to adapt.

Working with instruments in the way we’ve been discussing strikes me as experimental. Not in the sense that “experimental music” is usually used, but in the sense that working with an instrument whose behavior is altered is actually an experiment—the musical implications of its behavior are unknown. The composer has a hypothesis (“This might sound cool.”) that he wants to test. Results aren’t necessarily evaluated empirically, but rather aesthetically (“Does this actually sound cool?” or “Will this make for an interesting piece?”). As with actual science, results can vary. Negative results are possible.

But there are also surprises to be found by following through with the experiment. A simple idea I have played with on the EMvibe is as follows: pitch detection is used to toggle notes on and off. A struck note is sustained by the EMvibe until struck again. Improvising on the instrument when it’s set up this way is interesting because it doesn’t take long to lose track of what notes have been struck and how many times. It can become like a game of whack-a-mole to try to silence the instrument. Notes that are left hanging need to be dealt with both musically and physically. This creates a kind of creative friction between the performer and the instrument where the instrument itself seems to have some agency. And this leads to ideas that my conscious mind could not have thought of.
This ability to configure the way an instrument responds is not unique to actuated acoustic instruments; indeed, that is the nature of composed instruments. But the immediacy of the response of an actuated acoustic instrument stemming from the fact that the instrument itself—and not a loudspeaker—diffuses the sound, offers not only new sounds and new ways of interacting with the instrument, but also a new perspective on the instrument itself.

Andrew McPherson’s Magnetic Resonator Piano is currently the most highly evolved actuated acoustic instrument. After spending considerable time with McPherson’s music it struck me that perhaps working with the Magnetic Resonator Piano had changed the way he thought about the piano. When asked about this he responded in an email as follows:

Yes, the MRP definitely changed how I thought about writing for piano. I’m not a pianist (I studied until age 12) and until this piece I was quite reluctant to write for piano. I felt like between the challenge of writing idiomatic music and the weight of all that history, I didn’t know where to begin. I built the MRP partly to get over my aversion to piano writing, since I thought if I changed what the piano was “about,” I might find it easier to come up with a personal take. But the funny thing was that in the process of all that, I completely fell in love with the piano as it exists normally. The MRP got me thinking a lot about color and timbre, and a lot of that transferred over to my regular piano writing.

Working with actuated acoustic instruments isn’t merely a quest for new sounds, but for new ways of thinking. By exploding the notion of what acoustic instruments can do and what performers can do with those instruments, this nascent field offers potential beyond the novel technologies and sounds. These instruments have the potential to be sources of inspiration and new ideas for composers, to afford new expressive tools for performers, and to fascinate audiences.
Donald Norman writes, “Each technology poses a mind-set, a way of thinking about it and the activities to which it is relevant, a mind-set that soon pervades those touched by it, often unwittingly, often unwillingly.” After almost two years of development on and work with the EMvibe I feel like I am only beginning to scratch the surface of its creative potential. Even so, it has already changed how I think about making music both as a performer and a composer. And the EMvibe is just one of many potential instruments. I am eager to see the where this field leads, what other instruments are created, and how those instruments lead to unprecedented new mind-sets.

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Bibliography


