NORTHWESTERN UNIVERSITY

IN/OUT/IN: Feedback Systems in Music

A DISSERTATION

SUBMITTED TO THE GRADUATE SCHOOL

IN PARTIAL FULFILLMENT OF THE REQUIREMENTS

for the degree

DOCTOR OF MUSIC

Field of Music Composition

By

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EVANSTON, ILLINOIS

(May 2010)

ABSTRACT

IN/OUT/IN: Feedback Systems in Music

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A feedback system is defined as a modifying system whose output is returned to its own input. In its most basic conception, feedback operates in nearly every conceivable field of study, from astrophysics to evolutionary biology to economics to philosophy. Within the last half-century or so, artists of all types have begun to incorporate feedback into their works, in literal (mechanical) and non-literal (metaphorical) ways. As a technique, feedback has proven to be especially fruitful ground for artistic exploration due to its unusual applicability to both the conceptual and structural aspects of the medium to which is is applied. This document discusses the use of feedback in the sonic arts—by rock musicians, composers and sound artists—focusing on the three main categories of musical feedback: acoustic feedback (sympathetic resonance) as found in the music of Steve Reich, Robert Ashley, and Alvin Lucier (including an extensive spectral analysis of *I am sitting in a room*), mathematical feedback systems as used by Tom Johnson and myself, and so-called "no-input" electronic feedback systems pioneered by David Tudor. In addition, the relation of feedback to indeterminacy and improvisation, the concept of "noise," the acoustic properties of resonance and reverberation, the mathematical foundations of network and complexity theory, and the philosophical/aesthetic implications of feedback in music are discussed.

Contents

Chapter 1: The Idea(s) of Feedback

Concept, Philosophy, Aesthetics

To begin with, let us define the term *feedback* as a situation in which the output of a system is returned to the input of that same system (thus, the output is *fed back* into the system). This situation results in a potentially infinite recycling of information through the modifying factor of the system. The term *feedback loop* is frequently used to refer to the cyclical nature that results in such a scenario. The evolution of a feedback system depends primarily on the modifying factor, which may either be reinforcing (resulting in *positive feedback*) or inhibiting (resulting in *negative feedback*). The colloquial phrases *vicious circle* and *virtuous circle* are both examples of positive feedback, highlighting the point that the term does not imply a subjective assessment of the merits of the system, but simply that the results are continuously modified *in the same direction*. In a negative feedback system, the results tend to gravitate towards a condition of equilibrium or stasis. One example would be a clock pendulum, where the gravitational pull and the inertia continuously counteract or *inhibit* each other, resulting in a condition of homeostasis.

It is revealing to note that the most common usage of the term feedback—as a form of critical evaluation between people—is also an example of a feedback process as defined above. A person's behavior (the output) is subjected to evaluation (the modifying factor) and altered accordingly (the altered output). Depending on the nature of the criticism, the behavior may be reinforced by encouragement (positive feedback) or discouraged by disapproval (negative feedback). This type of *social* feedback is analogous to the more rigid physical and mathematical systems that do not involve human subjectivity.

Feedback in its most basic conception operates in nearly every conceivable field of study, from evolutionary biology to economics to philosophy. The tangled complexities and philosophical conundrums that arise when dealing with feedback networks are only beginning to be explored. Within the last half-century or so, artists of all types have begun to incorporate feedback into their works, in literal (mechanical) and non-literal (metaphorical) ways. As a technique, feedback has proven to be especially fruitful ground for artistic exploration due to its unusual applicability to both the conceptual and structural aspects of the medium to which is is applied. This paper will focus primarily on the use of feedback in the sonic arts—by rock musicians, composers and sound artists.

From a philosophical perspective, feedback has offered several points of entry for modern artists. Parallels have been drawn between the infinite looping of feedback networks and certain philosophical and religious notions of humanity's role in the universe. Many religions—particularly Eastern religions such as Buddhism and Hinduism—view existence as being cyclical and infinite. This is distinct from the prevailing Western view of time as flowing irreversibly forward, from presumed beginning to presumed end.[1] Modern artists—particularly composers—have a long history of involvement with Eastern philosophy. John Cage and Philip Glass, for example, have based many of their compositional techniques on concepts taken from

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[1] An example of a *feedforward* system, in which information moves irreversibly through the system from input to output. Feedforward systems typically display predictable, hierarchical behaviors (as distinct from feedback networks which are typically unpredictable and non-hierarchical).

Eastern philosophy. Philip Glass's use of additive rhythms is an example of algorithmic feedback which can be viewed not only in relation to his interest in traditional Indian musical structures, but also Hindu ideas of reincarnation and transmutability.

Scientific advances in the second half of the 20th-century have brought a uniquely Western take on ideas espoused by Eastern transcendental thought. The theory of relativity, quantum mechanics, and chaos theory each paint a picture of the universe in a state of relativistic flux, where the tiniest subatomic particles and the vastest cosmic structures are reflected in each other in a tangled complex of unknowable linkages. The study of feedback networks reveals a similar situation wherein the simplest structural architecture yields incomprehensibly complex and chaotic results. Feedback has allowed scientists and artists alike to create a simulacrum of scientific experience, one that is both amenable to creative manipulation and beyond our capacity to construct. Earle Brown describes this disconnect as, "a state of seeming unrelatedness." According to Brown, "there is no such thing as chaos except as a saturation point of comprehensibility, which is somewhere between here and infinity...and always sliding about between."[2]

In addition to the more general philosophical ideas that feedback has provided, it has also shed light on aspects more directly applicable to artistic themes and concerns. For example, the peculiar relationship of cause-and-effect between the different nodes of a hypothetical network calls into question traditional notions concerning the subject/object dialectic. In a feedback loop, cause becomes effect and effect becomes cause. Many modern artists have recognized in this curious state of affairs an effective strategy

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[2] Earle Brown, "Transformations and Developments of a Radical Aesthetic," Current Musicology 67/68 (2002), 43.

for subverting an out-dated, hierarchical approach previously taken as axiomatic. The cause-and-effect mechanics of feedback have parallels in artistic notions of subject and object, as well as *figure* and *ground*. In visual art, for example, an artwork in which the figure and the ground are interchangeable is referred to as being *recursive*. In his book *Gödel, Escher, Bach*, Douglas Hofstadter explains that, "the 're' in 'recursive' represents the fact that both foreground and background are cursively drawable —the figure is 'twice-cursive.'"[3]

In Scott Kim's ingenious drawing *FIGURE-FIGURE Figure,* the black and white areas are identical, both spelling out the word "figure." As viewers, we experience an uncanny and somewhat awkward sensation as we attempt to make sense of the picture. The drawing sabotages our instinctual tendency to create structural hierarchies, to distinguish "important," or primary, material from secondary material. A conflict arises within our minds: are we meant to pick one, black or white, to fulfill the role of foreground material? Should we rapidly switch back and forth between the two? We are so used to creating these hierarchical divisions that it doesn't seem possible to consider the black and white portions as being equally important at the same time. This peculiar sense of destabilization is an inherent quality in many recursive systems, be they visual, mathematical, or acoustic.

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[3] Douglas Hofstadter, *Gödel, Escher, Bach* (New York: Basic Books Inc., 1979), 67.

"FIGURE-FIGURE Figure": A recursive drawing by Scott Kim in which the foreground and background are identical.[4]

Feedback networks have provided substantial compositional fodder for those who espouse a breakdown of traditional ideas of what form and material should both *do* and *be*. The mechanics of feedback allow for a situation in which the composer can set in motion a process of his chosen specifications, the results of which are often beyond his capacity to predict (much less control). Initial systematic conditions determine the nature of the material in the piece as well as how that material will unfold over time. For some, this situation undermines the very point of artistic endeavor. Theodor Adorno, for example, would describe a piece composed in this manner as a, "work of art without content." Music that embodies, "the epitome of a mere sensuous presence, would be nothing more than a slice of empirical reality. The unmediated identity of content and

[4] Hofstadter, *Gödel, Escher, Bach*, 69.

appearance would annul the idea of art."[5] Others see in such art a perfect aesthetic representation of a society acclimating itself to a post-relativistic, post-modern philosophical condition. Form and material, figure and ground, signifier and signified, would come together as a, "new immanent body."[6] In *The Responsibility of Forms*, Roland Barthes writes that, "Modern listening no longer quite resembles listening to indices and listening to signs. What is listened to here and there is not the advent of a signified, object of a recognition or of a deciphering, but the very dispersion, the *shimmering* of the signifiers."[7]

Process, Complexity, Emergence

Feedback networks, when implemented in real-time, are a unique example of a so-called musical *process*, a concept expounded upon in Steve Reich's landmark essay, *Music as a Gradual Process*. By using a systematic process or algorithm to govern the development of a musical work (as opposed to subjective notions of taste and intuition) composers were able to "hand over the reins" and let the music work itself out. Musical processes had in fact been around for centuries; 15th and 16th century mensuration canons being one obvious precursor.[8] In the late 20th century, however, the technique came to imply a quasi-political aesthetic philosophy that called into question previously established roles of artist, listener, and performer. At the core of musical processes in

[5] Theodor Adorno, *Sound Figures* (Stanford: Stanford University Press, 1999), quoted in Paul Hegarty, *Noise/Music: A History* (New York: The Continuum International Publising Group Inc., 2008), 35.

[6] Hegarty, *Noise/Music*, 33.

[7] Roland Barthes, *The Responsibility of Forms: Critical Essays on Music, Art, and Representation* (New York: Hill and Wang, 1985), 245.

[8] Reich frequently cites Medieval composers, particularly Perotin, as being an influence on his concepts and techniques regarding musical process.

general is a will toward discovery, a desire to circumvent traditional egocentric decision-making and create something—inasmuch as is conceivably possible—"outside" of ourselves. As Reich explains, "once the process is set up and loaded it runs by itself."[9] The process composer aims to close the gap between the composer and the listener, placing himself in the audience, content to be merely the one who "sets up and loads" the music.[10]

In this sense the aims of process music are identical to those of so-called *chance* or *indeterminate* music. David Toop remarks that compositional techniques such as process and chance, "question the definition of music as a cultural production distinguished from noise or unorganized sound by human agency and intentionality."[11] Such compositional designs strive to sabotage the intentionality of their creators and realize Busoni's declaration that, "music was born free, and to win freedom is its destiny."[12] However, although chance and process music share this same conceptual ideal, the musical works themselves typically differ in very direct and immediately perceivable ways. Process pieces are often characterized by (intentionally) extreme predictability and a gradual metamorphosis of a relatively limited amount of materials. Chance music is by definition the antithesis of predictability (unless, of course, it could be said to be predictably unpredictable). Feedback-based music lies somewhere in

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[9] Steve Reich, "Music as a Gradual Process," in *Writings on Music* (New York: Oxford University Press, Inc., 2002), 34-35.

[10] There is of course an unavoidable irony in Reich's subsequent fame and critical praise as a result of his "ego-less" compositions, not to mention the famously caustic disagreement between Reich and Glass over who should take credit for what particular musical innovation.

[11] David Toop, "The Generation Game: Experimental Music and Digital Culture," in Christoph Cox and Daniel Warner, *Audio Culture* (New York: Continuum, 2008), 240.

[12] Ferruccio Busoni, *Three Classics in the Aesthetics of Music* (New York: Dover, 1962), 84.

between these two dichotomies of "ego-less" music. In one sense, feedback music operates exactly as a Reich-ian process piece would; the algorithm or network is set up and loaded and the piece runs by itself. In another sense, the mathematical complexity that often emerges from a feedback network results in a highly chaotic and indeterminate-sounding piece.

This seeming paradox of feedback music to employ highly mechanistic—even simplistic—means to achieve strikingly unpredictable ends is a characteristic of *complex systems*. Complex systems, when referred to in the context of *complexity theory*, consist of "many elements interacting according to very simple laws but giving rise to surprisingly complex overall behavior."[13] Peter Beyls, in his article *Chaos and Creativity*, offers a connective model for constructing such a system:

1. Design a simple agent, i.e. definition of a native character.
2. Create initial random affinities between agents.
3. Specify global constraints acting as global parameters.
4. Provide gestural input to particular groups of agents.[14]

As Beyls's model clearly demonstrates, complex systems can be constructed from remarkably simple structures. A distinction should also be made between systems that are themselves complex and those that display complex (or *complicated*) behavior. Complex systems necessarily contain self-referential "linkages" (step 2 in the Beyls model), resulting in a multitude of constantly fluctuating pathways of information. While complex systems typically display complex behaviors, it is also possible to construct a system which displays complex behavior but which is itself not technically complex. For

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[13] Peter Beyls, "Chaos and Creativity: The Dynamic Systems Approach to Musical Composition," *Leonardo Music Journal*, Vol. 1, No. 1 (1991): 31.

[14] Beyls, "Chaos and Creativity," 35.

example, a feedforward system consisting of several strings of computations moving in parallel could conceivably produce a result that is superficially very similar to that of a feedback network. Nevertheless, such a system is inherently deterministic and linear. Agostino Di Scipio notes the distinction between the types of complexity used in various stochastic pieces by Xenakis and what he terms "observing systems":

> Xenakis's stochastic rules (as used in a number of works)...did not implement an "observing system" (term coined by Heinz von Foerster). The composer's algorithm, or "mechanism," could not change its own behavior based on a knowledge of its own previous states. Indeed, the spectrum of probabilistic functions allows for only one global property to emerge, an ineluctable rush toward the average final point or "mean state value" (i.e., *stochos*, destination, destiny).[15]

Di Scipio's analysis betrays a tendency toward a somewhat anthropomorphic view of recursive systems (a tendency which is hardly unique to Di Scipio). The recursive system has the ability to "observe" itself, it has a "knowledge" of its own history. The non-recursive system, though still highly complex and unpredictable, is doomed to march, zombie-like, toward its "final destiny." Obviously, such a characterization is at least partially tongue-in-cheek; no respected mathematician or scientist would seriously claim that a complex system is literally "alive." The capacity for such systems to display spontaneous organization links feedback with the scientific fields of artificial intelligence and *emergence*.

When we perceive patterns of organization that were not explicitly programmed into a complex system, the system is said to exhibit emergence.[16] These patterns of

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[15] Agostino Di Scipio, "Systems of Embers, Dust, and Clouds: Observations after Xenakis and Brun," *Computer Music Journal*, Vol. 26, No. 1 (2002): 25.

[16] It should also be noted that while all complex systems necessarily contain some element of feedback, they do not all necessarily display emergent qualities.

organization, however unpredictable, are identified as having some structural quality which is said to be "irreducible to its constituent parts." Examples include the construction and architecture of anthills, sand dunes, and the overall shapes and motions in swarms of birds or schools of fish. Within each of these examples one can easily identify two primary levels of behavior: the rapid, microscopic local-level interactions of the "building blocks" (ants, grains of sand, individual birds and fish) and the overall behavior of group *as a whole*. The great fascination of emergent systems is that there really is no *as a whole*; there is no single cognitive entity which controls the large-scale behavior of the group.

Composers have been especially inspired by such systems, probably because they are so easily adapted into a musical context. Many of the "sound mass" compositions of Ligeti and Xenakis are directly modeled on emergent phenomena. Ligeti's technique of micropolyphony in pieces such as *Atmospheres* and *Lontano* consists of an accumulation of local level—often canonic—rhythmic and pitch behaviors into enormous conglomerations of sound. Similarly, Xenakis has created musical simulations of gas dispersion, in which individual note-attacks become metaphorical molecules, in pieces such as *Pithoprakta* and *Metastasis*. While these pieces are clearly inspired by the behaviors of certain emergent systems, they are not themselves examples of such a system (which is not to say that this in any way diminishes their artistic merit). Xenakis and Ligeti are clearly in control of the size and behavior of their particular "swarms," and are guiding them with conscious aesthetic intent. It is only through the direct incorporation of feedback systems into their music that composers have been able to create *truly* emergent works. Feedback has given composers the means to go beyond mere simulation of these fascinating and beautiful phenomena. Brian Eno, a composer who frequently incorporates emergent systems into his ambient works, eloquently expresses the structural and philosophical affinities between emergence and the arts**:**

> As the variety of the environment magnifies in both time and space and as the structures that were thought to describe the operation of the world become progressively more unworkable, other concepts of organization must become current. These concepts will base themselves on the assumption of change rather than stasis and on the assumption of probability rather than certainty. I believe that contemporary art is giving us the feel for this outlook.[17]

Improvisation vs. Indeterminacy

As mentioned earlier, the exponentially complex patterns of information flow in feedback networks lead to situations that are, for all intents and purposes, indeterminate. From a philosophical standpoint the indeterminacy that arises from a complex system is of a completely different type than that which arises from using the *I Ching*. For novelist/critic Umberto Eco, the distinction links the idea of the "open work" with current scientific perspectives:

> In this general intellectual atmosphere, the poetics of the open work is peculiarly relevant: it posits the work of art stripped of necessary and foreseeable conclusions, works in which the performer's freedom functions as part of the discontinuity which contemporary physics recognizes, not as an element of disorientation, but as an essential stage in all scientific verification procedures and also as the verifiable pattern of events in the subatomic world.[18]

Eco is referring here to indeterminacy with regard to performance practice, as frequently found in the works of Christian Wolff, Earle Brown, et. al. However, the

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[17] Brian Eno, "Generating and Organizing Variety in the Arts," in Cox and Warner, *Audio Culture*, 233.

[18] Umberto Eco, *The Open Work* (Cambridge: Harvard University Press, 1989).

connection between the subatomic world and musical indeterminacy is every bit as applicable to feedback systems as it is to performance practice. In fact, feedback systems are a unique and strikingly direct connection between indeterminacy and interpretive performance technique, or *improvisation*.

The distinction between these two terms—*indeterminacy* and *improvisation*—is often presented from a sociopolitical viewpoint. Each one is typically associated with its respective genre, being either classical/experimental, or jazz, and never the twain shall meet. As John Zorn—both a classical composer and improvising jazz saxophonist—points out, this is a tenuous and often arbitrary boundary: "I can understand why composers at that time felt compelled to justify their work with intellectual systems and words such as 'aleatoric,' 'intuitive,' and 'indeterminate.' They were trying to justify to the critical community that this was not 'improvised' music."[19] British free guitarist Derek Bailey points out that even interpretations of the same term can bear the fingerprints of these two distinct cultural lineages. He notes that Wadada Leo Smith, in his book *Notes: 8 Pieces*, "speaks of free improvisation almost exclusively as an extension of jazz," while Cornelius Cardew, in "Towards an Ethics of Improvisation," considers it "mainly in terms of European philosophy and indeterminate composition."[20]

Despite the occasional contentious differences of opinion regarding indeterminacy vs. improvisation, the two approaches share, at their core, a willful relinquishment of control. Historically, it was precisely by demonstrating a complete control of form and material that a composer made his or her reputation. This notion

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[19] John Zorn, "The Game Pieces," in Cox and Warner, *Audio Culture*, 197.

[20] Derek Bailey, *Improvisation: Its Nature and Practice in Music* (New York: Da Capo, 1992).

reached its pinnacle at the height of the modernist movement, when even the most minute detail, down to individual dynamic and articulation markings, had to be justifiable within the operating principles of the work. As Bailey colorfully points out, "Nowhere is the concept of form as an ideal set of proportions which transcend style and language clung to with such terrified tenacity as by the advocates of musical composition."[21]

Leaving aside the political overtones of such an approach, experimental composers and improvisors alike find that there is a costly price to pay for the complete subjugation of form and material. Experimentalism rejected the Gödel-esque trap of modernism: that by committing themselves to a mastery of concept and technique in their music, modernists were confining their art to a relatively small and uninteresting space (namely, the conscious mind of the artist). Counter-arguments against the chance music of the New York School and the free-improvisation of Ornette Coleman and other "non-jazz" groups such as Cardew's Scratch Orchestra are neither hard to come by or entirely lacking in merit. Despite exaggerated similarities in drop-the-needle comparisons between, say, Cage's *Music of Changes* and any number of total serialist piano works by Boulez or Babbitt, Cage's chance procedures created musical results that could never have arisen from rational, deterministic compositional decisions. But was this fact alone enough to merit decades of music based on dice rolls? How many more versions of *Music of Changes* could be written, and what would be gained from them?

As for improvisation, the most common criticism was that, contrary to claims of spontaneity and discovery, performers were essentially rearranging formulaic, patterned

[21] Bailey, *Improvisation*.

clichés they learned from countless hours of practicing along with old Charlie Parker recordings. British composer/improvisor Gavin Bryars, like John Zorn, is particularly well-equipped to comment on the relative merits and pitfalls the two approaches. "Composing, I could reach conceptions that I could never reach in a limited, defined, performing time. I couldn't reach an equal conceptual excellence in improvising as in composing."[22] The real-time compositional demands of free-improvisation, rather than forcing the performer into a state of spontaneous creativity, pose the risk of achieving the opposite effect wherein the performer reverts to tried-and-true methods of considerably less "conceptual excellence." However, Bryars primary concern with improvisation is even more poignant in that it links improvisation with what many improvisors claimed to be modernism's cardinal sin: self-glorification. "One of the main reasons I am against improvisation now is that in any improvising position the person creating the music is identified with the music. The two are seen to be synonymous. The creator is there making the music and is identified with the music and the music with the person."[23]

The application of complex networks and feedback systems in music has the ability to address all of these issues and criticisms simultaneously. In many pieces based on feedback systems, most notably in David Tudor's electronic pieces, there arises a situation in which the performer is improvising within (or sometimes *against*) an indeterminate context. A complex web of interconnections is constructed, leading to unpredictable and chaotic sonic results. The composer/performer then interacts with

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[22] Bailey, *Improvisation*.

[23] Bailey, *Improvisation*.

the system, attempting (with highly-varying degrees of success) to "guide" the system in a particular direction. Christopher Burns and Matthew Burtner describe this peculiar fusion of composition and improvisation in their article "Recursive Audio Systems":

> Once the system is established, improvisation becomes an essential mode of compositional exploration. The unusual parametrizations of feedback systems, including their high degree of dependence upon the current state and contents of the system, necessitate an investigative approach.[24]

From a certain perspective, such a situation counteracts the most common criticisms of the three approaches of structured composition, chance, and improvisation. The banality of chance is countered by the rigid mechanics of the network. The pedantic egoism of modernism is countered by the high degree of indeterminism and flux, as well as the improvisatory actions of the composer. Lastly, the formulated clichés of free improvisation are thwarted by the interaction of the performer with an "instrument" that is thoroughly beyond his or her control.

Thus, in feedback, composers and improvisors may have found a common ground on which to engage in Cage's "purposeful purposelessness or a purposeless play."[25] Modern improvisors like Evan Parker look to feedback rather than intuition as the guiding principle in their improvisations. Parker describes the methodology behind his solo saxophone improvisations in an interview with David Toop:

> I set up loops of stuff and then observe the loop and listen closely to the loop and say ah, now I'll emphasize that note, or now I'll bring out that difference tone, or I'll try and put something underneath it in relation to that or on top. Gradually the center of attention in

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[24] Chrisopher Burns and Matthew Burtner, "Recursive Audio Systems," *Leonardo Music Journal*, Vol. 13 (2003): 73.

[25] John Cage, *Silence* (Hanover: Wesleyan University Press, 1961), 12.

> the loop shifts somewhere else. The loop suddenly is a different loop. It's something that's still bearing fruit for me.[26]

In his solo improvisations, Parker achieves an elegant balance of traditional notions of improvisation based on spontaneous emotional expression and deliberate simulations of cybernetic control systems. Later in the interview, he addresses feedback specifically:

> It's the key notion of the 20th century. I'm not an expert on cybernetics but bringing an ability to generalize about feedback is a 20th century phenomenon. Before that there were specific applications but I don't think there was a general awareness of how many control systems can be analyzed in terms of the feedback between inputs and outputs. It's certainly high on my list of analytical tools.[27]

Proponents of recursive audio systems are drawn to the uncertain boundary between chaos and control, as well as the ambiguous distinction between composer and performer. How logical it is, then, that the one artist who is most responsible for both the conceptual and technical advancement of musical feedback is a virtuoso pianist renowned for his mechanistically accurate realizations of chance compositions. As a pianist, David Tudor simultaneously embodied two polar extremes: his performance technique demanded a precisely deterministic causal relationship between physical action and sonic result, while his chosen genre of indeterminism and chance strove above all to remove intentionality and control from the music. In his own works, however, these two "Tudors" are at last comfortably reconciled. Deliberate actions yield unpredictable results; virtuosity and failure can coexist. While Tudor's live electronic performances were frequently described as dazzling displays of virtuosity, "his physical

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[26] Toop, "The Generation Game," in Cox and Warner, *Audio Culture*, 243.

[27] Toop, "The Generation Game," in Cox and Warner, *Audio Culture*, 243.

contact with the electronic components resulted in a spectrum of sound possibilities, all a step removed from the physical impulse that had caused them."[28] Built in to the architecture of feedback is a distancing—a failure of communication—that occurs between the composer, the performer, and the instrument. For Tudor, this "aesthetic of failure"[29] results in a new level of interaction that is absent in modernism, chance, and improvisation alike. Though he remained a loyal Cage supporter to the end, he delicately admits as much himself in his 1972 article "From Piano to Electronics":

> I wasn't interested in playing a game or dealing with a set of finite circumstances but rather in the fact that the world was completely open, and through a set of finite circumstances one could be led into something completely open. This was always uppermost in Cage's works, but a lot of the pieces I was getting seemed to be more attracted by the idea of structures rather than by the possibilities these open up.[30]

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[28] Tamara Levitz, "David Tudor's Corporeal Imagination," *Leonardo Music Journal*, Vol. 14 (2004): 61.

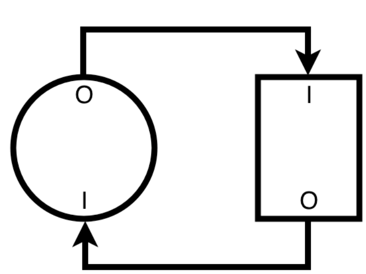
[29] Kim Cascone, "The Aesthetics of Failure," *Computer Music Journal*, Vol. 24 (2000): 12-18.

[30] David Tudor, "From Piano to Electronics," *Music and Musicians* (August 1972): 24.

Chapter 2: Network Types

As we have seen, there are few limitations on the size, design, and medium of a particular feedback network. From the gravitational orbits of the celestial bodies, to a stock market crash, to a patch of slime mold, feedback networks are almost so varied and ubiquitous as to defy focused scientific research. A detailed analysis of feedback networks can only be undertaken with regard to a specific instance, with only the most general conclusions being applied to the phenomenon as a whole. In this chapter we consider some of the types of feedback networks that can be applied to music.

All feedback networks, musical and otherwise, are constructed of two basic elements: *nodes* and *connections*. The *nodes* are the active elements in the network, the places where information gets processed. The *connections* govern where the information is sent after it is processed by the node. For example, in guitar feedback, as used to great effect by such performers as Jimi Hendrix and Pete Townshend, there are two nodes and two connections. The nodes are the guitar pickup, which converts sound vibrations in the air into electrical current, and the guitar amplifier, which converts the electrical current back into sound at a greatly increased volume. The connections are the guitar cable, which takes the electrical current to the amplifier, and the air, which carries the sound waves from the amplifier to the guitar pickup. A diagram of such a network might look something like this:



In this diagram, "O" stands for "output" and "I" stands for "input." The circle represents Pete Townshend's guitar and the rectangle represents his enormous Hiwatt amplifier stack. The different shapes used to depict the nodes are not meant to represent any real-life geometric corollaries, but rather to distinguish between the two types of nodes most frequently found in feedback systems used in music: *variable* and *invariable*.

An *invariable* node is one in which information is processed in a consistent and predictable way. Whatever information goes into an invariable node is subjected to the same transformation each time, whether it be sound amplification, division by 2, or gravitational inertia. In musical situations this is often a piece of equipment, as it is in guitar amplification, but as we will see there are many examples of music that use different kinds of invariable nodes. A *variable* node is a node in which the manner or degree to which the information is processed changes. When Pete Townshend flails his guitar, pushing and prodding it against the amplifier, he is essentially *performing* with one node of the feedback network. By moving his guitar into different positions, Townshend is controlling the amount of signal that is being fed back into the pickup, as well as which resonances are being emphasized. Therefore, the amount of processing that occurs at that node is not consistent, as it is in the amplifier.[1] This is an important distinction to make in recursive audio systems since composers frequently use a balance of variable and invariable nodes to achieve the desired levels of chaos and control.

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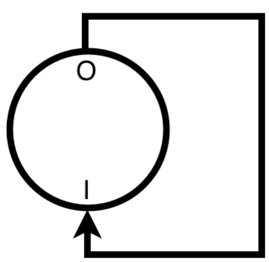
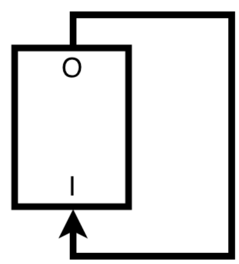
[1] The variability in a variable node can occur as a result of some performative act (as in the case of Pete Townshend) or it can be built into the design of the node itself, not requiring any real-time human intervention.

Single-Node Networks

The most basic type of feedback network found in music is the single-node network. In a single-node network there is only one transformational process at work, and only one possible connection: from the output back to the input. Thus, there are only two possible scenarios of single-node networks in music: the variable single-node network and the invariable single-node network.



Variable Single-Node Network



Invariable Single-Node Network

As a real-world musical scenario, the variable single-node network barely qualifies as musical feedback. The most obvious example is a solo improvisor—someone making real-time musical decisions based on reactions to what he or she has just played. We have already discussed the saxophonist Evan Parker, who conceives of his solo improvisations as a feedback loop in which, over time, "the center of attention....shifts somewhere else."[2] By his own account, Parker is making a conscious effort to think of himself (of his brain, perhaps) as a *processor of information*, focusing on a specific aspect of his sound and slowly transforming it until some new aspect appears which can subsequently be transformed.

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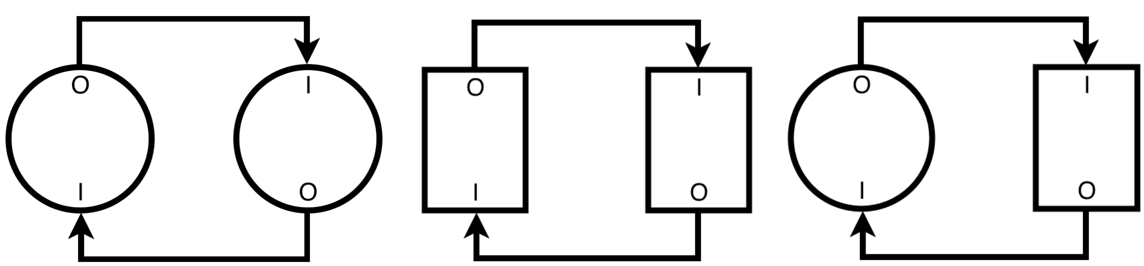
[2] Toop, "The Generation Game," in Cox and Warner, *Audio Culture*, 243.

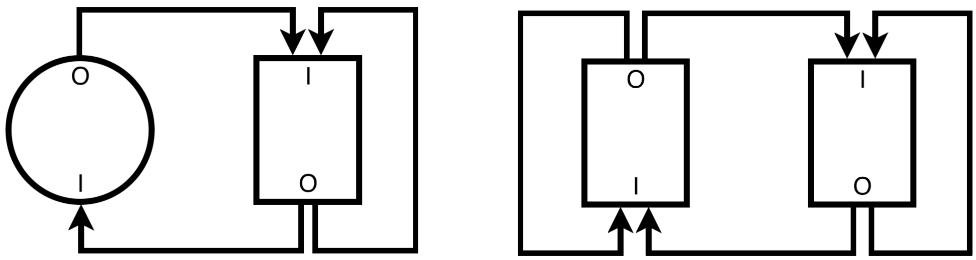
There are few cases of invariable single-node networks in music, as this will almost always result in an undesirably high degree of predictability. One notable example, which will be discussed at length later, is Alvin Lucier's *I am sitting in a room*. In this piece there is only one node—the reverberant space itself—which transforms the sound in precisely the same way each time. As expected, the result is highly linear, and, to a certain extent, predictable. The success of the work is due the selection of the node—resonant reverberation—and the infinitely intricate complexities that it yields.

Multiple-Node Networks and Multiple-Input Nodes

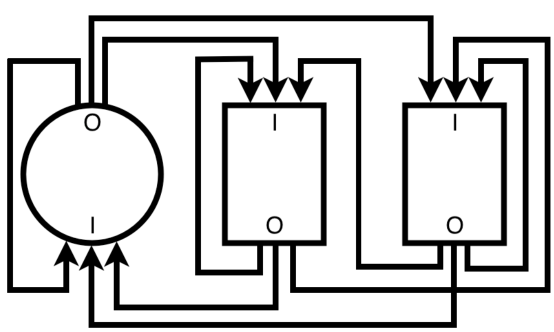
As one would expect, the addition of more nodes to a network greatly increases the number of potential information paths within the network. First, let us consider all of the possibilities of a 2-node network. There are three possibilities of combinations of variable and invariable nodes in a 2-node network: variable-variable, invariable-invariable, and variable-invariable.



In addition to these new combinations, nodes in a multiple node network also have the capacity to be sending or receiving information from more than one output or input simultaneously. These *multiple-input nodes* allow for an exponential increase in possible information loops. The following diagram depicts two different possibilities of a 2-node network with multiple-input nodes.

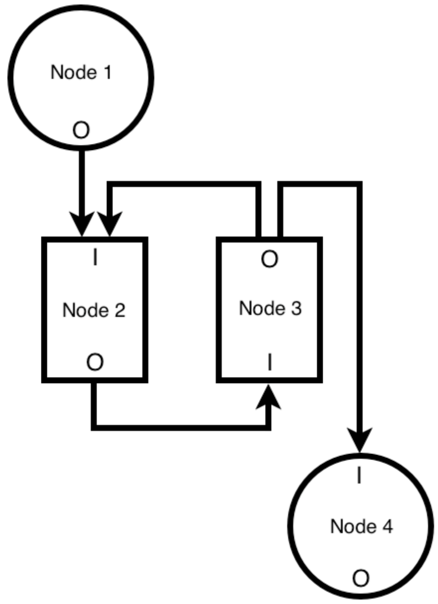


The diagram on the left represents a variable-invariable 2-node network in which the invariable node is a multiple-input node. Information can now flow through one of two possible feedback loops: the 2-node loop between the variable and the invariable node and the 1-node loop from the output of the invariable node back to its own input. In the diagram on the right, both of the invariable nodes in the network are multiple-input nodes. Since all of the possible pathways between the two nodes are connected, this network can be referred to as a *fully-interconnected network*. In a fully-interconnected 2-node network there are three possible information loops: one 2-node loop and two 1-node loops. In the following diagram of a fully-interconnected 3-node network, we can see that there are now nine connections (the number of connections in a fully-interconnected network is always the square of the number of nodes).



It is important to distinguish between the number of *connections* and number of *loops*, or information pathways. When describing the behavior of a feedback network, the main concern is how many loops there are, not how many connections (although the two are clearly linked). A single loop in a fully-interconnected 3-node network could use one, two or three connections. For example, a loop of information that leaves the output of any node in the network and returns immediately to the input of that same node only requires one connection. However, a different loop in which the output of the first node passes through both the second and the third nodes before returning to the input of the first node requires three connections. In this way, the total number of possible loops within a multiple-node network quickly becomes difficult to manage. Of course, for most practitioners of musical feedback, this is entirely the point.

In all of the diagrams above, every node in the network is *recursive*, that is, information coming from the output of the node will inevitably return to the input of that same node (either directly or after passing through another node). However, many feedback networks contain *non-recursive* or *feedforward* nodes which serve to pass information on to another part of the network. An example of a musical situation in which this might arise is when a filter or effect—reverb, for example—is applied to the global output of a recursive network. This processed output can then be passed on to another set of nodes, or, more typically, sent out to the speakers. Consider a hypothetical 4-node network in which a microphone is picking up the sounds made by a saxophonist (node 1) and sending them into a distortion pedal (node 2), which is connected in a feedback loop with a delay pedal (node 3). The output of that loop is then sent into the headphones of a dancer (node 4), who translates the sound in to bodily motion. In this scenario there are two non-recursive nodes (the saxophonist and dancer) and two recursive nodes (the distortion pedal and the delay pedal).



Nodal Ordering and Loop Math

When calculating the number of possible loops within a given network, the issue of nodal ordering must be taken into account. The order or sequence of the nodes through which information passes may or may not matter depending on the situation. This is due to the exact same principle underlying the arithmetic order of operations. Consider a mathematical network of three nodes: the first node adds 3 to whatever number it receives, the second node subtracts 2 from whatever number it receives, and the third node adds 10 to whatever number it receives. In this 3-node network there are two possible loops for information to follow:

loop 1: N1 -> N2 -> N3 -> N1 ...
loop 2: N1 -> N3 -> N2 -> N1 ...

Since the loop is continuous, it is arbitrary which node we start with. If we input the number 5 into each of these two loops, we can see that after one complete cycle the output is exactly the same, despite the fact that the nodal ordering is different.

loop 1: 5 -> 8 -> 6 -> 16 ...
loop 2: 5 -> 8 -> 18 -> 16 ...

However, if we change the operation of node 2 from subtract 2 to divide by 2 we can see that nodal ordering does affect the output after one cycle of the loop.

loop 1: 5 -> 8 -> 4 -> 14 ...
loop 2: 5 -> 8 -> 18 -> 9 ...

This very simple mathematical law which is known to all grade-school children is a critical element in how musical feedback systems work. A clear musical analog of this "order of operations" is frequently encountered by electric guitarists who use numerous effects pedals. As most experienced guitarists will attest to, the order in which the pedals are connected together in the signal chain greatly affects the resulting sound. For example, consider an effects chain consisting of a wah-wah pedal and a distortion pedal. There are two possible signal chains: 1) from the guitar to the wah-wah to the distortion pedal to the amplifier or 2) from the guitar to the distortion pedal to the wah-wah to the amplifier. In the first scenario, the wah-wah (being essentially a band-pass filter) will first emphasize certain frequencies in the guitar signal. These emphasized frequencies will then receive a greater amount of distortion coming out of the distortion pedal (since distortion pedals apply more distortion to higher signal levels). In the second scenario, the level of distortion will be applied to the whole guitar sound evenly before being filtered by the wah-wah, leading to noticeably less fluctuation in the level of distortion applied to the overall sound.

In order to calculate the number of possible feedback loops in a network, the following factors must be considered: the number of nodes, the connections between the nodes, and the relevance of nodal ordering. There is no simple formula to encompass the infinite number of network combinations. However, if we limit our possible networks to those that are both fully-interconnected and either completely *unordered* (in which the sequence of the nodes through which information passes is irrelevant) or completely *ordered* (vice versa) some mathematical formulas can be applied to determine the number of possible information loops within the network.

If we think of a fully-interconnected unordered network as a set of *n* nodes, the number of possible loops is simply the sum of all of the possible subsets of the network. Since order is irrelevant, all that needs to be considered is the number of possible *combinations* of nodes. In the following formula, *n* is the total number of nodes in the network and *r* is the number of nodes in the subset:

$$\frac{n!}{r!(n-r)!}$$

Using the *combination formula*, we can quickly calculate the total number of feedback loops in a given unordered network by adding up the number of subsets, from all of the 1-node loops (which will always be *n*) to all of the *n*-node loops (which will always be one). Therefore, in a fully-interconnected unordered 4-node network there are a total of fifteen information loops, with four 1-node loops, six 2-node loops, four 3-node loops, and one 4-node loop.

To calculate all of the possible feedback loops in a network in which the order of the nodes *does* affect the output we must use a hybrid of the *combination formula* and the *permutation formula.*[3] First, we must calculate all of the different combinations of nodes we can find using the combination formula given above. Then we must calculate all of the permutations of the set with *one less node* than the set we are dealing with. This is because, since we are dealing with feedback *loops*, all of the possible permutations can be derived with the same node as the starting point (thus eliminating one possible permutable node). The formula for deriving the number of possible feedback loops for a subset of any ordered network is:

$$\frac{n!(r-1)!}{r!(n-r)!}$$

The chart on the following page shows all of the possible feedback loops for fully-interconnected networks with up to 7 nodes as well as a breakdown of the number of loops per nodal subset. While there is admittedly little practical use for such a reference chart, it does shed some light on the behavioral tendencies of the various possible feedback systems that can be constructed in a musical situation.

[3] The permutation formula alone would work if not for the fact that the information is looping, thus two or more possible permutations may be duplicates of each other: i.w. the nodal sequence 1-2-3-4 is the same as 2-3-4-1, 3-4-1-2, and 4-1-2-3 in a feedback loop.

1-Node Network

	Unordered	Ordered
1-Node Loops	1	1
Total Loops	**1**	**1**

2-Node Network

	Unordered	Ordered
1-Node Loops	2	2
2-Node Loops	1	1
Total Loops	**3**	**3**

3-Node Network

	Unordered	Ordered
1-Node Loops	3	3
2-Node Loops	3	3
3-Node Loops	1	2
Total Loops	**7**	**8**

4-Node Network

	Unordered	Ordered
1-Node Loops	4	4
2-Node Loops	6	6
3-Node Loops	4	8
4-Node Loops	1	6
Total Loops	**15**	**24**

5-Node Network

	Unordered	Ordered
1-Node Loops	5	5
2-Node Loops	10	10
3-Node Loops	10	20
4-Node Loops	5	30
5-Node Loops	1	24
Total Loops	**31**	**89**

6-Node Network

	Unordered	Ordered
1-Node Loops	6	6
2-Node Loops	15	15
3-Node Loops	20	40
4-Node Loops	15	90
5-Node Loops	6	144
6-Node Loops	1	120
Total Loops	**63**	**991**

7-Node Network

	Unordered	Ordered
1-Node Loops	7	7
2-Node Loops	21	21
3-Node Loops	35	70
4-Node Loops	35	210
5-Node Loops	21	504
6-Node Loops	7	840
7-Node Loops	1	720
Total Loops	**127**	**2372**

Chapter 3: The Acoustics of Feedback

> God was a first-rate acoustical engineer. We have been more inept in the design of our machines. For noise represents escaped energy. The perfect machine would be a silent machine: all energy used efficiently.[1]

The word *feedback* carries a disproportionate lexicological burden in that it is commonly used to refer to three related yet distinct situations: one evaluative, one mathematical, and one acoustic. This chapter deals with the third type: acoustic feedback (also known as the Larsen effect after the Danish scientist who first discovered its principles). The boundaries of a thorough investigation of the properties of acoustic feedback encompass a rich array of topics, ranging from early scientific investigations into the properties of sound waves, to anatomical dissections of the human ear, to ancient and contemporary architectural design, to electrical engineering.

Sympathetic Resonance

The most logical place to begin a discussion of acoustic feedback is with the pioneering investigations into acoustics made by the 19th-century German scientist Hermann Helmholtz. In 1863, Helmholtz published his highly influential book, *On the Sensations of Tone as a Physiological Basis for the Theory of Music*, in which he methodically explains both the physical mechanics of sound as well as our biological capacity for experiencing it. Central to his theory is the now accepted description of sound as a variation in pressure that moves through the air as a traveling wave. In the first chapter of his book, Helmholtz distinguishes between two categories of sound: *tone*

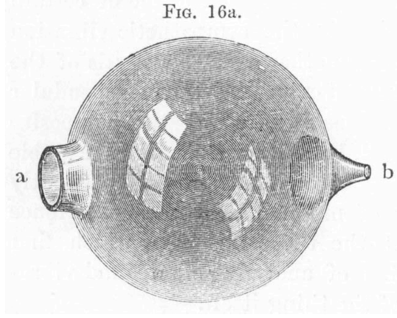
[1] R. Murray Schafer, *The Soundscape* (Rochester: Destiny Books, 1994), 207.

and *noise*. "The sensation of musical tone is due to a rapid periodic motion of the sonorous body; the sensation of a noise to non-periodic motions."[2] The periodicity of the vibration results in a perceivable *frequency* which we term the pitch of the tone. Helmholtz recognized that when a particular periodic vibration is acted upon by another vibration of the same frequency, the amplitude (or volume) of the vibration is reinforced in what he calls *sympathetic resonance*:

> This phenomenon is always found in those bodies which when once set in motion by any impulse, continue to perform a long series of vibrations before they come to rest. When these bodies are struck gently, but periodically, although each blow may be separately quite insufficient to produce a sensible motion in the vibratory body, yet provided the periodic time of the gentle blows is precisely the same as the periodic time of the body's own vibrations, very large and powerful oscillations may result. But if the periodic time of the regular blows is different from the periodic time of the oscillations, the resulting motion will be weak or quite insensible.[3]

In order to investigate the properties of sympathetic resonance, Helmholtz fashioned numerous glass orbs and tubes of various shapes and sizes, objects now known as Helmholtz resonators. A typical Helmholtz resonator (as seen below) has a large open cavity whose size corresponds to a calculated resonant frequency, and a small protrusion at one end which is to be inserted into the ear canal for observation.

Fig. 16a.



[2] Hermann Helmholtz, *On the Sensations of Tone* (New York: Dover Publications, 1954), 8.

[3] Helmholtz, *On the Sensations of Tone*, 36.

In addition to affecting the volume of a particular sound, Helmholtz recognized that sympathetic resonance could be applied to issues of consonance and dissonance (as a consequence of sympathetic vibrations among upper partials) as well as the physiological mechanisms we use to hear. Careful dissections of the human ear revealed many direct parallels between the biological functions involved in the perception of sound and the ingenious inventions Helmholtz had constructed in his laboratory. At times he describes the ear almost as if it is nothing more than a series of amplifiers and transducers. Explaining the functions of the auditory ossicles (the hammer, anvil, and stirrup), he writes:

> The mechanical problem which the apparatus within the drum of the ear had to solve, was to transform a motion of great amplitude and little force, such as impinges on the drumskin, into a motion of small amplitude and great force, such as had to be communicated to the fluid in the labyrinth.[4]

The issue of sympathetic resonance arises regarding the "elastic formations"—the nerve fibers—in the cochlea:

> When a compound musical tone or chord is presented to the ear, all those elastic bodies will be excited, which have a proper pitch corresponding to the various individual simple tones contained in the whole mass of tones, and hence by properly directing attention, all the individual sensations of the individual simple tones can be perceived.[5]

In this way, the cochlea behaves as a collection of thousands of tiny Helmholtz resonators, each one waiting to be triggered by a vibration with a frequency that corresponds to its own resonance. The "very large and powerful oscillations" that Helmholtz observed in his glass orbs and in the elastic fibers of the cochlea were quite

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[4] Helmholtz, *On the Sensations of Tone*, 134.

[5] Helmholtz, *On the Sensations of Tone*, 148.

literally acoustic feedback in action. Sympathetic resonance is simply the observable result of the process of a sound wave being reintegrated into itself in a loop.

Acoustic Architecture

Sympathetic resonance, especially when combined with the effects of acoustical reverberation (the persistence of sound in an acoustical space due to reflection) can lead to dramatically different acoustical spaces. As far back as the historical record extends, people have observed and manipulated these effects. Evidence of this lies in the ruins of ancient buildings whose curious architectural designs reflect the intentional manipulation of resonance and reverberation. In the Mayan Pyramid of Kukulkán at Chichén Itzá, for example, there are staircases that, "produce chirplike echoes that bear an uncanny resemblance to the call of the Mayans' sacred bird, the resplendent Quetzal."[6] Another example is the ancient Babylonian myth in which, "there are hints of a specially constructed room in one of the ziggurats where whispers stayed forever,"[7] likely an effect caused by its abnormally reverberant acoustics. In yet another instance, Vitruvius, the 1st-century B.C. Roman writer and architect, envisioned the placement of tuned resonating chambers in theaters to increase the aesthetic qualities of the sound:

> Hence in accordance with these enquiries, bronze vases are to be made in mathematical ratios corresponding with the size of the theatre. They are to be so made that, when they are touched, they can make a sound from one to another of a fourth, a fifth and so on to the second octave. Thus by this calculation the voice, spreading from the stage as from the centre and striking by its contact the hollows of the several vases, will arouse an

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[6] Barry Blesser and Linda-Ruth Salter, *Spaces Speak, Are You Listening?* (Cambridge: MIT Press, 2007), 59.

[7] Schafer, *The Soundscape*, 89.

increased clearness of sound, and, by the concord, a consonance harmonizing with itself.[8]

Extant examples of acoustically-minded architecture abound. Most notable are the many Catholic cathedrals whose hard walls and vast spaces imbue them with an overpowering resonance, designed to symbolize the vastness and depth of the divine.

Although it might not occur to one at the outset, these ancient architects of Mayan pyramids, Babylonian ziggurats, and Roman theaters are early users of acoustic feedback. In all of these examples, the architectural design serves to reinforce the sounds that occur within the space. Highly reflective walls and vast expanses of air allow the sound waves to bounce around, *feeding back* into themselves. In the cases of the Mayan Pyramid and Vitruvius's theater, specific frequencies are selected and reinforced by way of sympathetic vibration. These ancient architects are, in a very real way, *composing* with space; they are literally creating sounds tailored to a specific aesthetic goal. Contemporary acoustic architects, on the other hand, most often aim for exactly the opposite effect. Almost all modern concert halls and convention centers contain sound deadening features designed to eliminate both resonance and reverberation. In *The Soundscape,* the definitive study of the history of acoustic ecology, R. Murray Schafer laments the need for he what terms a "negative acoustic design" in an increasingly noisy world. “In a quiet world, building acoustics flourished as an art of sonic invention. In a noisy world it becomes merely the skill of muting internal shuffles and isolating incursions from the turbulent environment beyond.”[9]

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[8] Vitruvius, *De Architectura* (Pisa: Giardini, 1975).

[9] Schafer, *The Soundscape*, 222.

Gain

While the experiments of the likes of Vitruvius and Helmholtz dealt directly with the phenomenon of self-reinforcing sound waves, it wasn't until the advent of electrical sound amplification that what we now commonly refer to as acoustic feedback was able to occur. In the vastest of cathedrals, reverberation times rarely last more than ten seconds. This is due to the unavoidable interference of naturally occurring sound dampening factors. Even the most highly polished stone walls will inevitably absorb a small amount of sound with each reflection, and what's left will either be diffused into open space or slowly dampened by air resistance. Despite what the Babylonian myth told, there never existed a place in which, "whispers stayed forever." What was needed to push sound past the point of no return was *gain*.

Gain, in the broadest sense, is a measure of the reinforcement strength of any feedback system. It is the ratio of the intensity or magnitude of the output of a system to its input, and can refer to a variety of units of measurement. Feedback systems with a gain significantly less than one will quickly grind to a halt. One example that we have already discussed in this chapter is natural reverberation. In natural reverberation, the input (a church organ) is significantly louder than the output (the echo). As a result the system delivers diminishing returns and quickly fades to silence. Conversely, in a feedback system with a gain greater than one, each subsequent output is greater than the previous, leading to a runaway situation which can quickly become unstable.[10] A

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[10] A famous popular example of a runaway positive feedback loop is the 1961 film *The Absent Minded Professor* in which the main character invents a rubber-like substance called "Flubber" which gains energy every time it bounces. Since the output (the height of the second bounce) of the system is greater than the input (the height of the first bounce) the gain is greater than one and the system quickly becomes unstable (thus providing the majority of the comedic material for the film).

common example of a feedback system with a gain equal to one (also referred to as *unity* gain) is a pendulum clock, whose each subsequent "swing" is exactly the same magnitude and speed as the previous one. Feedback systems with a gain equal to one display a steady-state or *stable* behavior pattern. Another example is the orbits of the planets in our solar system.

What typically occurs in an acoustic feedback system is that a closed loop containing a sound source (usually a microphone or pickup) and an amplifier has sufficient gain (i.e. greater than one) to enter into a continuously self-reinforcing state.[11] In acoustic feedback systems, gain can be a measurement of decibels (itself a dimensionless unit), voltage, or current. Though the mathematical calculations will vary depending on the unit in question, the crucial threshold ratio of one remains the determining factor in the behavior of the system.

Since sound pressure is inversely proportional to the distance of the source ($p = 1/d$), the farther away the microphone is from the amplifier the lower the gain ratio will be. When the source moves within a certain threshold distance from the amplifier (a distance dependent primarily on the level of amplification, the sensitivity of the microphone, and the directional correlation between them), a self-reinforcing sonic loop will occur without the need for additional sonic input. The resulting frequency response is dependent upon several factors, and as a result is often highly unstable.

Acoustic feedback systems tend to resonate at specific frequencies determined by the Barkhausen stability criterion, which states that these frequencies fulfill two necessary requirements: 1) the gain at that frequency is equal to one and 2) the phase

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[11] Since acoustic feedback requires that energy be *added* to the system in order to bring the gain above one, it was not possible until after the invention of electrical amplification.

shift around the loop is either zero or an integer multiple of 360 degrees. Whether or not a specific frequency fulfills these requirements depends on many other external factors, including the specific frequency response pattern of the microphone, the initial sonic input, the rate of movement of information through the loop (also called the *delay time*), the temperature and humidity of the surrounding air, and, as we have already mentioned, the distance between and directional alignment of the microphone and the amplifier. Because many of these factors are in a constant state of flux and highly interdependent, the resulting resonant frequency fluctuation can be rapid and extreme.

Most scientific research in acoustic feedback is carried out with the intent of finding ways to eliminate the phenomenon. Various strategies and inventions such as "adaptive filter modeling" and "automatic notching" have been devised to preemptively find and block potential feedback frequencies. However, the science and mathematics of acoustic feedback can also be exploited in more proactive ways. Many of the musicians discussed in this paper have intuitively manipulated the various parameters underlying feedback resonance in order to create interesting and novel sonic results. A more deliberately scientific approach to feedback music might systematically explore the variety of behavioral possibilities in a tightly controlled feedback system. On the other hand, it is after all the very fragility and unmanageableness of feedback that has attracted artists to it in the first place. To attempt to "tame the beast" so to speak might well be missing the point altogether.

Chapter 4: Feedback in Popular Music

While the diversity of types of feedback systems in popular music is significantly less than in experimental music—primarily restricted to so-called "guitar feedback"—its prevalence and aesthetic significance is arguably greater within the popular genre than in any other. This chapter discusses the history of the use of acoustic feedback in popular music, from its first tentative appearances on early blues records, to the cathartic feedback explosions of Jimi Hendrix and The Who, and finally to more contemporary examples of feedback as primary sonic material. The use of feedback systems in the context of popular music also broaches the subject of feedback as *noise*, a term with broad philosophical, aesthetic and political implications that can be related to popular and experimental genres alike.

The first uses of feedback on popular recordings are approximately concurrent with its incorporation into experimental music. Johnny "Guitar" Watson has been cited as the first person to record guitar feedback in his groundbreaking track "Space Guitar" (1954). Throughout the upbeat honky-tonk blues song, Watson displays an aggressively virtuosic playing style and a variety of new timbral effects for guitar. The guitar tone switches several times between a traditional "dry" sound and one with an extremely high degree of reverb (presumably the "space guitar" sound). While it is without question a pioneering recording with regard to guitar technique and record production, a close listening reveals none of the characteristic hum and squeal of actual acoustic feedback.[1] The unprecedented levels of reverb coupled with Watson's rapid-

[1] That is, acoustic feedback with a gain level greater than one.

fire articulation create a swirling and overwhelming aural effect without the actual occurrence of a self-propagating acoustic feedback loop.

Another strong contender for the first example of recorded feedback on a pop song is The Beatles' "I Feel Fine," released in 1964. The song begins with sustained bass attack which morphs into a 5-second crescendo hum culminating in a high-frequency squeal. In this case the presence of acoustic feedback is undeniable, and is supported by first-person accounts. Paul McCartney recalls the now famous incident as follows:

> We were just about to walk away to listen to a take when John leaned his guitar against the amp. I can still see him doing it...it went, 'Nnnnnnwahhhhh!" And we went, 'What's that? Voodoo!' 'No, it's feedback.' Wow, it's a great sound!' George Martin was there so we said, 'Can we have that on the record?' It was a found object, an accident caused by leaning the guitar against the amp.[2]

Whether or not "I Feel Fine" is a truly the *first* use of recorded feedback in a pop song may be impossible to determine. It is, however, quite likely that it is at least the first *intentional* use of feedback as a desirable sonic element. This shift from thinking of feedback as noise to be eliminated to thinking of it as an appealing sound with expressive potential paved the way for an drammatic rise in the use of feedback in subsequent years.

Feedback as Catharsis

The discovery of the expressive potential of guitar feedback conveniently coincided with the turbulent cultural climate of the mid-1960s. Especially in the United States (but in England as well), the controversial war in Vietnam, the sexual revolution,

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[2] Barry Miles, *Many Years From Now* (New York: Henry Holt, 1997).

and experimentation with drugs contributed to the development of a popular music style that expressed the anxieties and new-found freedoms of the youth movement. Guitar feedback, being (necessarily) loud and chaotic, became a perfect acoustic symbol for both the political discontent and the sexually-charged catharsis of the time.

The Who were the first band to use a significantly high degree of guitar feedback in their music, albeit usually only in live settings and at the end of the performance. The band became legendary for the destruction and sonic anarchy that they created on stage. Guitarist Pete Townshend would frequently end a show by smashing his guitar into the amplifier and leaving its shattered remains to shriek and howl for several minutes. For The Who, acoustic feedback provided a crucial link between the cathartic physical destruction of the instruments and the musical performance itself. As both the players and the audience become unleashed through the physicality of the performance, so too does the music through perpetually reinforcing amplification. As Paul Hegarty writes in his book *Noise/Music*:

> When Pete Townshend destroys his guitars, it initially comes from loss of control and the physical rendering of rage unleashed through aggressive performance, but in terms of sound, it is the loss of subjective control as feedback takes over – neither the band nor crowd can master this sound.[3]

As we have seen, the "un-masterability" of the sound is merely the result of complex interactions within a network of electroacoustical nodes. There is nothing inherently rebellious about feedback; it is science. The distinctive acoustic behavioral patterns that result when a microphone nears an amplifier become anthropomorphized and adopted by both the performers and audience.

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[3] Hegarty, *Noise/Music*, 60.

Perhaps the most celebrated example of feedback in popular music is Jimi Hendrix's rendition of *The Star-Spangled Banner* at the Woodstock music festival in 1969. Like The Who, Hendrix exploited the emotional expressivity of the chaotic nature of acoustic feedback. With *The Star-Spangled Banner*, however, Hendrix pursued a more directly political interpretation, as well as literal sonic representation. Howling glissandi, unpitched rumblings and hissing white noise interrupt the detuned melodic phrases of the anthem. The controversy surrounding the performance is in one sense rather obvious: the national anthem is considered, if not sacred, at least demanding of respect. Hendrix seemed to deny that respect, and to even show outright disrespect, through the sonic destruction to which he subjected the anthem. This interpretation, while likely intended by Hendrix himself, is not inherent in the sounds themselves. Rather, it is a cultural metaphor that we have created which equates feedback to noise and noise to rebellion. Acoustic feedback is *supposed* to be considered an accident—an acoustical failing. Placing it in the foreground is thus a celebration of failure and an endorsement of anarchy.

The irony of the juxtaposition of this "loss of mastery" with the national anthem—the musical symbol of the United States—is immediately apparent. Many people have also interpreted Hendrix's descending glissandi and grating "explosions" as sonic representations of bombs falling on Vietnam. Taking this into consideration, we can see that the feedback-as-metaphor in this case operates on three levels simultaneously: as the cathartic rebellion of youth, the loss of control of the government, and the violent destruction of war.

Feedback as "Music"

In more recent decades, some popular musicians have exploited the expressive potential of feedback for its own sake (that is, feedback as *sound* rather than feedback as *metaphor*). Guitarists have become increasingly adept at controlling both the pitch and volume of acoustic feedback, allowing them to "orchestrate" the sounds in a more traditionally musical fashion. This is typically achieved by dampening certain strings (usually all but one) and fretting the undampened string at a length corresponding to the desired pitch. The guitar string acts as a filter, allowing only certain frequencies (which can be easily and rapidly adjusted) to feed back. Unlike the "noisy" feedback used by Jimi Hendrix and Pete Townshend, controlled feedback can be quite pleasant and tranquil, with sustained, finely-tuned tones.

Most famous for their use of controlled feedback is the Irish rock group My Bloody Valentine, led by guitarist/singer Kevin Shields. Their 1991 album *Loveless*—which notoriously took two years of studio work to complete and nearly bankrupted their record label—uses layers upon layers of multi-tracked guitar feedback to create a dense, almost claustrophobic texture that is both consonant and melodic. Through practiced and controlled playing techniques, Shields was able to reduce the parametrical fluctuations in his feedback networks to a bare minimum, resulting in tones of unprecedented stability. By removing the chaotic fluctuations from the sound, Shields also removed the chaotic *metaphor* from the music. All that is left are the acoustic properties of the sound itself. The contribution of *Loveless* is that it validated feedback as a musical "instrument" equal to any other.

Another notable event in guitar feedback (perhaps not coincidentally also in 1991) was the release of Neil Young's live album *Arc-Weld*. The album included a 35-minute track of guitar feedback edited together from various concerts in a continuous montage. Young's performances with his band Crazy Horse frequently included long stretches of feedback-drenched drones at crushing volumes. Young took The Who's idea—the sonic annihilation of the end of a song—and expanded it past the point of emotional catharsis into the territory of pure sound. This boundary, while perhaps indiscernible in the context of the live performance, is intentionally underlined by Young by the editing and release of the montage.[4] Listening to the recording, the "rock" has been completely removed; there is no beat, no singing (apart from the occasional howl), no "music" in the traditional sense. There is only feedback as musical sound.

Albums like *Arc-Weld* and others such as Lou Reed's *Metal Machine Music* reveal the spuriousness of the boundary separating so-called popular music from experimental music. In these cases the distinction seems to be based primarily on the rest of the artist's output rather than the work in question. In recent years a new genre of "noise music" has developed of which acoustic feedback is an essential sonic component. Contemporary noise artists such as Merzbow, Boredoms, Whitehouse and Oval draw as much influence from experimental composers like John Cage and David Tudor as they do from rock artists like The Velvet Underground and Sonic Youth.

[4] Reportedly at the suggestion of Sonic Youth's Thurston Moore, with whom Young was touring at the time of the recordings.

Chapter 5: Feedback and Noise

> Enlil heard the clamour and he said to the gods in council, “The uproar of mankind is intolerable and sleep is no longer possible by reason of the babel.” So the gods in their hearts were moved to let loose the deluge.
> —from The Epic of Gilgamesh (c. 3000 B.C.)[1]

Noise has always had a powerful capacity to disturb and disrupt. The reasons for our aural sensitivity are partly biological and partly cultural. Anatomically, our ears differ from our eyes in two significant ways: they cannot close (there are no "earlids"), and, while they can localize external sounds, they do not have the capacity for directed spatial focus. These two traits contribute to a total susceptibility to acoustic stimulus from any direction at any time. In addition, evolutionary biology suggests that our innate discomfort with loud and "noisy" sounds aided the survival of our species by allowing for quick and forceful reactions to potentially dangerous unseen sources.[2] Evidence of this theory can be seen in the everyday acoustic behavior of wildlife, whose barks, growls, roars, and hisses serve to warn would-be threats of imminent danger.

In *The Soundscape*, R. Murray Schafer proposes that, "silence as a condition of life and a workable concept disappeared sometime toward the end of the thirteenth century."[3] Luigi Russolo, in his 1913 manifesto *Art of Noises*, argues for a later date, claiming that, "ancient life was all silence. In the 19th century, with the invention of machines, Noise was born.”[4] Both Schafer and Russolo agree, though with radically

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[1] Schafer, *The Soundscape*, pg. 189.

[2] Eugene Morton, "On the Occurence and Significance of Motivation-Structural Rules in Some Bird and Mammal Sounds," *The American Naturalist*, Vol. III No. 981 (1977).

[3] Schafer, *The Soundscape*, pg. 258

[4] Luigi Russolo, *The Art of Noises* (New York: Pendragon, 1986), 23.

different qualitative assessments, that machines are the primary contributors of noise in the modern age. As one of several examples provided in support of this hypothesis, Schafer charts the steady increase in decibel levels of police and ambulance sirens over the decades:

> We have measured the siren on a 1912 vintage vehicle at 88 to 96 dBA at 3.5 meters. By 1960 siren intensity had risen to 102 dBA at 5 meters. The United States is now manufacturing a yelping siren for police car use which measures 122 dBA at 3.5 meters.[5]

As overall noise levels increase, individual sounds that vie for attention must do so as well. Here is an example of a positive feedback system in the cultural arena, the results of which are the deafening urban environments we see in many of the world's largest cities.

Noise and Music

Though we have become remarkably adept at the creation, abatement and manipulation of noise in our environment, a concrete definition of what noise is remains ambiguous. It is usually defined according to its relevance to two distinct areas: sound and information. *The Oxford Dictionary of Science*, for example, defines noise as: 1) any undesired sound, and 2) any unwanted disturbance within a useful frequency band in a communication channel.[6] Sound noise and information noise sometimes coexist (as in the case of a detuned radio), but not always. Statistical noise (as can occur in a broad survey), data noise (satellite communications), and electronic noise (molecular-level thermal fluctuations in circuit boards) are all examples of silent noise. In these

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[5] Schafer, *The Soundscape*, pg. 167.

[6] *The Oxford Dictionary of Science, 5th ed.* (Oxford: Oxford University Press, 2005.)

cases, the "noise" is all of the mistakes, glitches, and residua that occur for a variety of reasons and that we invariably try to eliminate. The use of the term to describe such disparate cases as the Sex Pistols and erroneous GPS instructions is likely based on the shared characteristics of rapid fluctuation and unintelligibility.

In *The Soundscape*, Schafer proposes his own four definitions of noise based on common usage: 1) unwanted sound, 2) unmusical sound, 3) any loud sound, and 4) disturbance in any signaling system. Tellingly, three out of four of these definitions have a directly negative connotation: *un*wanted, *un*musical, *dis*turbance. Of the four, Schafer concludes, "probably the most satisfactory is still 'unwanted sound.' This makes noise a subjective term. One man's music may be another man's noise."[7] Indeed, beginning in the early 20th-century, various avant-garde composers such as Russolo, Pierre Schaefer, John Cage and Karlheinz Stockhausen embarked upon a conscious and systematic breakdown of what they considered to be the spurious categorical distinctions between noise and music. For one thing, noise offered a seemingly limitless supply of new timbres. New instruments such as Russolo's *intonarumori* and Cage's prepared piano were created. Recent advances in recording technology allowed composers to incorporate almost any observable sound into their compositions. However, the reason the debate over the distinction between noise and music was arguably the definitive debate of the 20th-century (even more so than the breakdown of tonality) had less to do with the *sound* of noise per se than the philosophical and socio-political ramifications of the *idea* of noise.

[7] Schafer, *The Soundscape*, pg. 182

For most people, the term "music" represented a quasi-sacred concept, the sole purpose of which was the express the emotional genius of its creators to the rest of the world. To defile that concept with base, meaningless *noise*, no matter how pleasant or acoustically sophisticated, was simply unacceptable. In addition, the incorporation of noise, which defied the clear quantification of the traditional 12-note equal-tempered musical system, represented an endorsement of a dangerous kind of artistic anarchy. Cage spells it out explicitly:

> Since the theory of conventional music is a set of laws exclusively concerned with "musical" sounds, having nothing to say about noises, it had been clear from the beginning that what was needed was a music based on noise, on noise's lawlessness.[8]

This brand of anthropomorphic symbolism led to an ideological battle over a definition of music that resonated in realms of thought beyond the acoustical. Most of all, noise became debated/attacked/justified on *political* terms (hardly the first time a musical concept met that fate).

Noise as Politics

In *Noise: The Political Economy of Music*, one of the first significant theoretical attempts to address the subject, French economist and scholar Jaques Attali deconstructs the cultural neuroses underlying the fierce opposition to the use of noise in music. For Attali, the perceived danger of noise is its inherent resistance to *order*: "With noise is born disorder and its opposite: the world. With music is born power and its opposite: subversion."[9] Noise in music lies outside of the established semantic code; it

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[8] John Cage, *M: Writings '67-'72* (Middletown, CT: Wesleyan University Press, 1973), foreword.

[9] Jacques Attali, *Noise: The Political Economy of Music* (Minnesota: The University of Minnesota Press, 1985), 6.

is meaningless. Not coincidentally, this was precisely the criticism that was leveled against Schoenberg's 12-tone system (and the reason that Schoenberg made such great efforts to incorporate his 12-tone system into historically and semantically established formal designs). It is in fact a necessary paradox of noise that it remains semantically undefinable. As Simon Reynolds observes, noise alternatively (simultaneously?) thrives and fails as a result of this paradox: “The pleasure of noise lies in the fact that the obliteration of meaning and identity is ecstasy (literally, being out-of-oneself). If noise is where language ceases, then to describe it is to imprison it again with adjectives.”[10]

It is in this perpetual limbo that noise music propels itself forward, constantly negating/redefining/recontextualizing itself. Strategies of subversion become academic techniques; what was shocking becomes nostalgic and quaint. However, it is precisely because of this failing that noise avoids the Orwellian trap that so many artistic revolutions fall into. Hegarty again: “Noise is on the side of revolt rather than revolution, as revolution implies a new order, and noise cannot be a message-bearer (other than of itself as message)."[11]

Noise = Failure = Feedback

Feedback is a particularly powerful tool of noise music in that it succeeds in being "noise" on multiple levels simultaneously. Acoustic feedback, as we have seen, is *necessarily* loud (one of Schafer's definitions of noise) and more often than not behaves

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[10] Simon Reynolds, "Noise," in Cox and Warner, *Audio Culture*, 56.

[11] Hegarty, *Noise/Music*, 125.

chaotically. Additionally, feedback fulfills Schafer's fourth definition of noise as a "disturbance in any signaling system." Feedback loops act quite literally as short circuits that undermine the linearity of the system in which they exist. Because information does not flow in a logical, sequential order, quite bizarre and "meaningless" results often occur. Feedback is therefore both *sonically* and *conceptually* noisy to an extent that few other musical situations can achieve.

The (mis)use of technology has been the primary methodology of noise musicians precisely because of this dual function as *unmusical sound* and *signal disturbance*. Hegarty generalizes this trend to musical misuse in general, including such non-technological strategies such as Cage's prepared piano pieces and various extended techniques in instrumental performance. The intentional misuse of machines (including musical instruments) liberates new sonic potential while undermining misguided faith in the inevitability of technological progress:

> Noise, and use of it, helps reduce the belief that machines are mere means to higher musical or conceptual goals. This is because it highlights material production of sound, and this is further signaled through technical limitations and incidental unwanted noises.[12]

Most feedback music, including many of the pieces discussed in this paper, operate in precisely the way that Hegarty describes here. In acoustic feedback, the "material production of sound" is revealed via a continual and cyclical subjugation of the same material through a particular architecture. Through this process the hidden "incidental unwanted noises" are foregrounded; the noise becomes the music.

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[12] Hegarty, *Noise/Music*, 27.

Chapter 6: Acoustic Feedback in Experimental Music

Where popular musicians from Albert Collins to Kurt Cobain used acoustic feedback in their music to evoke a mood of sexually-charged sonic anarchy, experimental composers—primarily Americans—were often drawn to the more sedately scientific qualities of the phenomenon. For them, acoustic feedback offered the potential for a new array of sounds and formal implications that needed to be experimented with, studied, and learned from. In this chapter we will discuss the use of acoustic feedback in two works by American composers: Steve Reich's *Pendulum Music* and Robert Ashley's *The Wolfman*.

Pendulum Music

Steve Reich's *Pendulum Music* is possibly the most direct and "pure" use of acoustic feedback in a piece of music. The score, actually a set of prose instructions, is as follows:

> **Pendulum Music**
> for microphones, amplifiers, speakers and performers
>
> 2, 3, 4 or more microphones are suspended from the ceiling by their cables so that they all hang the same distance from the floor and are all free to swing with a pendular motion. Each microphone's cable is plugged into an amplifier which is connected to a speaker. Each microphone hangs a few inches directly above or next to it's speaker.
>
> The performance begins with performers taking each mike, pulling it back like a swing, and then in unison releasing all of them together. Performers then carefully turn up each amplifiers just to the point where feedback occurs when a mike swings directly over or next to it's speaker. Thus, a series of feedback pulses are heard which will either be all in unison or not depending on the gradually changing phase relations of the different mike pendulums.
>
> Performers then sit down to watch and listen to the process along with the audience.

> The piece is ended sometime after all mikes have come to rest and are feeding back a continuous tone by performers pulling out the power cords of the amplifiers.[1]

All of the sounds produced in *Pendulum Music* are the result of the feedback between the swinging microphones and the speakers above which they are hung. There is nothing inherently different about the use of feedback in *Pendulum Music* and Jimi Hendrix's *Wild Thing* (to use one of several possible popular music examples)—the mechanics of the how the music is produced in both cases is identical. Specifically, both are examples of a two-node variable-invariable network in which sound waves are converted into electrical current, amplified, and converted back into sound, etc. Despite this foundational similarity the two pieces are radically different, both sonically as well as in the extra-musical content that they evoke.

One striking characteristic of *Pendulum Music* is that, as mentioned above, *all* of the sound in the piece is feedback. The feedback is not an accompaniment or complimentary element within a larger musical context; neither is it a by-product of some other primary sonic instigator. *Pendulum Music*, it could be said, is quite literally *pure* feedback, and, by extension, *about* feedback. As evidence of this, Reich makes an explicit effort in the score to remove as much of the human element as possible from the performance. The variations in the variable node in *Pendulum Music* are not the results of improvised gesticulations or choreographed movements, but rather, the linear,

[1] Steve Reich, *Pendulum Music* (London: Universal Edition, 1980).

predictable variations in a natural physical process.[2] These linear variations create sonic behaviors that are radically different from those heard in most examples of guitar feedback. At the beginning of the performance, short, chirp-like glissandi, separated by periods of silence (while the microphones are outside of feedback range) create interlocking, almost polymetric, rhythmic patterns. As the piece progresses, there is a gradual shift toward a denser texture (as the microphones spend more time in feedback range) as well as more consistent pitch material (as the parametrical variation determining the resonant frequencies of the system decreases). It is this linearity, this *predictability* that invites us as listeners to focus on the sound itself, rather than the performance. After releasing the microphones, the performers are asked to, "sit down to watch and listen to the process along with the audience." This seemingly trivial detail is, upon further reflection, quite revealing as to how Reich intends the piece to be interpreted. *Pendulum Music* is more a phenomenon that needs to be *observed*, than a performance that needs to be *communicated*.

In the same year that he composed *Pendulum Music*, Reich published a landmark essay entitled "Music as a Gradual Process." In this essay he discusses the formal characteristics of what became known as "process music." While the essay as a whole is not directly applicable to feedback, there are two points that Reich makes that are worth mentioning with regard to *Pendulum Music*. At the beginning of the essay, Reich proposes three non-musical situations as being analogous to the experience of performing or listening to a gradual musical process. One of these is, "pulling back a

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[2] As discussed in the first chapter of this paper, a pendulum is itself an example of negative feedback system in which gravity and inertia (and to a lesser extent wind resistance) are recursively interconnected. Thus, interestingly, in *Pendulum Music,* the negative feedback loop of the pendulum swing "drives" the positive feedback loop of the microphones and speakers.

swing, releasing it, and observing it gradually come to rest." Based on the article alone, it is fairly clear that Reich is referring not to swinging microphones suspended from the ceiling, but merely to a common playground swing. However, it is obvious enough that with *Pendulum Music* Reich achieved a literal manifestation of his hypothetical analogy. Later in the essay he discusses the relationship between form and content in process music:

> Material may suggest what sort of process it should be run through (content suggests form), and processes may suggest what sort of material should be run through them (form suggests content). If the shoe fits, wear it.[3]

No other piece of Reich's more than *Pendulum Music* achieves such a direct union of form and content. It is not clear in this case whether the content suggested the form (i.e. that Reich's desire to use feedback suggested swinging microphones as a way to create sonic variation) or that the form suggested the content (that Reich imagined [as we know he already had] a piece that used swings and realized that microphone feedback would be an effective way of generating sound). Whatever the case, the use of acoustic feedback in *Pendulum Music* is at least indirectly implied in "Music as a Gradual Process."

The Wolfman

Robert Ashley's *The Wolfman*, composed in 1964 (four years before *Pendulum Music*), is one of the first published works to use acoustic feedback as the primary sonic material. The piece was written for the debut recital of a singer-friend of Morton

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[3] Reich, *Writings on Music*, 34.

Feldman's, but for reasons which are obvious to anyone who has heard the piece, it was not performed on the concert.[4] The piece was performed later in the year, however, at an avant-garde festival in New York, and soon gained a reputation as a "considerable threat to the listener's health."[5] From all reports performances of the piece are frighteningly, painfully, and disorientingly loud.

The Wolfman is scored for solo amplified singer with tape accompaniment.[6] Like *Pendulum Music*, the "score" is a set of prose instructions for the setup and method of performance. The singer is instructed to improvise within a very narrowly defined set of rules. The vocal sound is deconstructed into four "variable components" of pitch, loudness, vowel ("tongue forward as far as possible to tongue retracted as far as possible"), and closure ("jaw closed/lips pursed to jaw open/lips drawn as far as possible").[7] Each vocal "phrase" lasts the length of one full breath, during which the singer gradually alters one of the four components while keeping the other three steady. The singer may choose which component to vary, in which direction they wish to move (i.e. from loud to soft, from open mouth to closed mouth, etc.) and how far along the range of variation they wish to move. The only other requirement is that each consecutive phrase must vary a different component than the phrase before. This performance methodology is strikingly similar to that of Alvin Lucier's *Silver Streetcar for*

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[4] Feldman was actually asked to write a piece for the occasion, but for whatever reason did not want to, so he asked Ashley to take on the task. Ashley claims that he wrote *The Wolfman* knowing full well that there was no way the piece would not be performed on the recital.

[5] Robert Ashley, "Cut and Splice 2005," *BBC*, http://www.bbc.co.uk/radio3/cutandsplice/wolfman.shtml

[6] Since the accompanying tape parts in *The Wolfman* function primarily as textural supplements and are not directly involved in creating acoustic feedback, we will exclude them from our discussion of the piece and focus instead on the live performance elements.

[7] Robert Ashley, *The Wolfman*, Alga Marghen Plana-A, 2002. CD.

the Orchestra (1988), in which a triangle player is asked to gradually vary one parameter of the sound (speed and loudness of the tapping, location and pressure of the dampening fingers, etc.) before switching to another parameter. Not coincidentally, the triangle in *Silver Streetcar* is also amplified to an unusually high degree. The purpose in both cases is to allow for a full exploration of the sonic qualities of the "instrument." Ashley provides the following schematic of a single vocal phrase in the performance instructions:

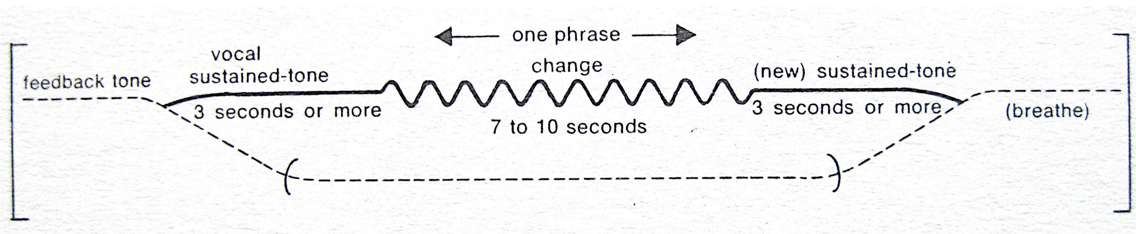

Fig. 1

The vocal sounds are amplified by a standard vocal microphone and loudspeakers, which Ashley instructs is to be set at the "highest possible level of amplification before feedback occurs." The singer (or an assistant) can also vary the level of amplification during the performance through the use of a potentiometer control. Like the vocal sounds, the level of amplification must be varied according to specific guidelines:

> Between each vocal phrase and before the first phrase and after the last one the singer or his assistant should increase (gradually) the amplification of the microphone signal until a steady feedback sound is produced. The transitions between the feedback sound and the vocal sustained-tones that begin and end the phrases should be as smooth and ambiguous as possible.[8]

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[8] Ashley, *The Wolfman*.

In this way, *The Wolfman* attempts to fuse a continuum between the so-called "primary" sonic material of the singer and the "secondary" or "noise" material that is the feedback. One of the most interesting aspects of the work is that, despite its abrasive cacophony, the piece is fundamentally about nuance and delicateness. The sounds themselves seem to nervously flutter in and out of feedback in a perpetual balance beam act. For Ashley, it is almost as if the extreme volume is merely a necessary byproduct of the mechanics of the piece:

> Reviewers, listeners and, indeed, some interpreters, I have been told, have understood *The Wolfman* as a person "screaming into the microphone". This couldn't be farther from the truth. The vocal sounds in the performance have to be probably the softest vocal sounds ever performed in public. Otherwise, the vocal sounds would 'block' the feedback and the two kinds of sound would alternate in the performance—singing, feedback during breathing etc.[9]

In the ideal performance of the work, the two sound events—the singing and the feedback—would, to the extent that is possible, meld into one. However, Ashley takes this idea this one step further and links the idea of feedback with the vocal production itself. The performance instructions insist quite emphatically that the tongue must at all times be touching the roof of the mouth. This allows, Ashley says, for a "certain amount of acoustical feedback to be present 'within' the sounds produced by the voice." He does not elaborate further on what exactly he means by this, but it seems likely that the feedback that he is referring to here is sympathetic resonance. As we have already discussed, the phenomenon of sympathetic resonance, which will always occur in closed spaces (with the possible exception of an anechoic chamber), is itself an example of acoustic feedback. In a performance of *The Wolfman* with sufficiently loud

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[9] Ashley, "Cut and Splice."

volume, the room itself will become an active participant in the piece, sculpting resonances and creating dynamic spatialization effects. As Ashley describes it, "full room feedback...allows even the smallest sound at the microphone to take on the illusion of moving around the room, depending on frequency and other aspects of the microphone sound."[10] Thus, as it was in *Pendulum Music*, multiple feedback loops are working in tandem to create the final sonic result.

It is significant that in both *The Wolfman* and *Pendulum Music* the aesthetic emphasis is on *sound* over theatricality or performance. Certainly both pieces have undeniably theatrical elements, and while it might seem a bit disingenuous to characterize especially *The Wolfman* as "sedately scientific," there are clear indicators that *suggest* a mode of listening based on observation rather than emotional communication. The audience is meant to focus, not on the antagonistic, cathartic "screams" of the speakers, but instead on the subtle interplay of competing resonant frequencies and dynamic spatialization effects. Ashley addresses the tendency to theatricalize the piece, which, he allows, is inherent in the material.[11] He cautions, however, that, "it is imperative ... that however the piece is to be presented theatrically, first attention should be given to realizing the sound intentions of the composition."[12]

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[10] Ashley, "Cut and Splice."

[11] Ashley proposes one possible interpretation of *The Wolfman* as a, "sinister nightclub vocalist, spotlight and all."

[12] Ashley, *The Wolfman*.

Chapter 7: I am sitting in a room

In Chapter 3 we discussed several examples of ancient architects who incorporated acoustic phenomena into the design of their buildings. Fascinated by the beautiful, ghostly ringing of natural resonance, they tried in vain to coax sounds to eternal life. Alas, no matter how hard they made the walls and no matter how large they made the space, they could not overcome nature's silencing force. Sound is energy and energy dissipates; all systems tend toward entropy. However, in 1969, Alvin Lucier finally managed to create his own magical room where the "whispers stayed forever." As it turns out, entropy can be overcome with a few tape recorders and a playback system.

Like many of Lucier's pieces, *I am sitting in a room* is half sound art, half science experiment. The entirety of the over 45-minute piece consists of 32 repetitions of a recording of the following passage of text, read by Lucier:

> I am sitting in a room different from the one you are in now. I am recording the sound of my speaking voice and I am going to play it back into the room again and again until the resonant frequencies of the room reinforce themselves so that any semblance of my speech, with perhaps the exception of rhythm, is destroyed. What you will hear, then, are the natural resonant frequencies of the room articulated by speech. I regard this activity not so much as a demonstration of a physical fact, but, more as a way to smooth out any irregularities my speech might have.[1]

These three sentences are both the explanation of the process and the material with which the process is "loaded" (perhaps the ultimate example of Reich's, "If the shoe fits wear it," approach to form and content). The irregularities mentioned at the end of the passage refer to Lucier's noticeable stutter, which is most apparent, fittingly, on the

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[1] Alvin Lucier, *I am sitting in a room*, Lovely Music, 1990. CD.

pronunciation of the word "rhythm." If we are to take this last sentence at face value (and, considering the potential psychological ramifications of something like a debilitating speech impediment, there is no reason not to) *I am sitting in a room* is an unquestionable success. However, despite the fact that it may not have been *intended* as a demonstration of a physical fact, the demonstration is hard to miss.

Two tape recorders were required to realize the work (one to playback and one to record each iteration). Despite the technical requirements of the work, the gear itself plays only a facilitating role in the piece, contributing nothing to the final sound.[2] The network schematic of the piece consists of a single invariable node with its output connected to its own input. The node is the room itself: the material and geometry of the enclosing surfaces, the volume of air between them, and, lest we forget, the man and the chair in the middle. The invariable operation that is applied with each iteration is the accumulation of resonance. The simplicity of concept and means belies the sonic complexity that unfolds over the course of the piece. *I am sitting in a room* is perhaps the quintessential example of musical feedback. It incorporates acoustic feedback in its most natural state—as sympathetic resonance—as the primary material in the loop. Thus, the feedback is feeding back: meta-feedback.

Lucier's works often present an uncompromising scarcity of materials with the goal of providing a more direct exploration of the core concept of the piece. He has famously remarked that the first thing he does when he begins work on a new piece is,

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[2] This is, admittedly, a highly debatable claim and is more a matter of perspective than objective truth. It is inevitable, especially considering the relative infancy of recording technology in 1969, that some sonic artifacts of the recording equipment became incorporated into the final recording. In addition, the frequency response curves of both the microphone and the playback speakers must have had a significant impact on the evolution of the material. These technological factors are rarely taken into account in discussions of the piece by Lucier or others. The fact is that most of us are willing to ignore such "imperfections" in deference to an otherwise pure phenomenological exercise.

"get rid of all the good ideas." In an interview with Douglas Simon (one of many published in Lucier's book *Reflections*), he reveals a similar methodology at work in the creation of *I am sitting in a room*: "My first impulse was to use various musical instruments playing a wide variety of sounds, but I tossed that idea out because it felt too 'composerly.'"[3] Lucier realized that any conceivable combination of notes and rhythms written for traditional (or non-traditional, for that matter) instruments would only have distracted from the core concept that he was trying to communicate. The decision to use speech accomplished two things that an instrumental version could not have: it focuses the listener on the process by equating the process with the material, and it provides the room with a rich spectrum impulse, thereby heightening the complexity of the sonic transformations. Speech, Lucier explains, "has a reasonable frequency spectrum, noise, stops and starts, different dynamic levels, complex shapes. It's ideal for testing the resonant characteristics of a space because it puts so much in all at one time."[4]

Even in a piece as severely minimal and demonstrative as *I am sitting in a room*, there are numerous compositional decisions that reflect the aims and aesthetics of the composer. The decision to use text, the composition of the text, and the selection of the room are reflective (no pun intended) of Lucier's desire to portray a natural phenomenon as directly and as *beautifully* as possible.

> I made a preliminary version of "I am sitting in a room" in the Brandeis University Electronic Music Studio, a small, bright, somewhat antiseptic room in which I never enjoyed being very much. It was filled with electronic equipment, and one wall consisted

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[3] Alvin Lucier, *Reflections* (Cologne: MusikTexte, 1995), 98.

[4] Lucier, *Reflections*, 98.

> of several large glass windows. The resonant frequencies got reinforced very quickly after the fifth or sixth generation, resulting in harsh, strident sounds.[5]

Despite the brash and uncompromising originality of the work, this quotation reveals a more conventional aesthetic sensibility. Both the phenomenon (the resulting resonances) and the process (the unfolding of those resonances) were subjected to a minimum standard of acceptance based on subjective notions of pleasingness and engagement. For the final recording, Lucier selected an apartment in Middletown with wall-to-wall carpeting and lots of drapes. This "architectural orchestration" allowed for a more gradual accumulation of resonance in a more aurally satisfying frequency range.

Frequency Analysis

The brilliant paradox of *I am sitting in a room* is that, while the basic mechanics of the physical laws at work are obvious to most people, the resulting sounds are of incalculable complexity. One might assume, as Lucier himself seems to, that a few specific frequencies—those that are geometrically predetermined by the dimensions of the room—would gradually and consistently increase in volume while all of the others fade to inaudibility. One might also assume that the so-called "rhythmic" content of the piece—the relative dynamic peaks and valleys—would gradually and consistently flatten out into a steady drone. However, a spectral analysis of the recording reveals that, while, in general, these assumptions are true, the reality is much more complex.

The evolution of resonances in *I am sitting in a room* can be loosely structured into the following four stages: "thinning phase" (iterations 1-8), "emergence phase

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[5] Lucier, *Reflections*, 98.

1" (iterations 9-14), "disruption phase" (iterations 15-22) and "emergence phase 2/ resolution" (iterations 23-32). The figures on pages 92-93 of the appendix chart the average amplitudes of the frequency content (from 0-12,000 Hz) per iteration for the first eight iterations. As any respectable acoustician would predict, these figures depict rapidly diminishing amplitudes in the higher frequencies. The first iteration (presumably Lucier's direct, unrecorded voice) contains a relatively strong frequency content all the way up to around 11,000 Hz. After just the first four iterations everything above 4,000 Hz has disappeared. After the next four, with the exception of one dwindling spike just below 2,000 Hz, the audible bandwidth has dropped below 1,000 Hz (a 10,000 Hz drop from the first iteration). This thinning of the upper frequencies is due to the faster absorption rates of high frequency sound waves as they travel through the air.[6] Simultaneously, we see a gradually increasing peak amplitude in the 200-400 Hz range from just below -40 db in the first iteration to over -30 db in the eighth. This is the first evidence of feedback at work. As resonances get added to resonances the decibels accumulate.

The figures on pages 94-101 show the average amplitudes of the frequency content up to 700 Hz for all 32 iterations. This narrower frequency range allows us to visualize the individual resonance spikes and their evolution over the course of the piece (after about the 9th iteration there is no more audible sound above 700 Hz, so the diagrams are, for intents and purposes, complete). Phase 2 (aka "emergence phase 1") is characterized by the gradual appearance of six major frequency peaks at 199 Hz, 241

[6] A result of the viscosity of the medium (in this case, air) through which sound travels. Higher frequency sound waves cause air molecules to vibrate faster than lower frequency sound waves, and this requires a greater transference of energy from the sound wave to the air molecules. Thus, high frequency sound waves run out of energy and become quieter much faster than low frequency sound waves.

Hz, 294 Hz, 318 Hz, 351 Hz and 417 Hz. The exact point at which these peaks begin to exhibit their dominance is ill-defined, but is somewhere around iteration 9. While the peak amplitudes of these frequencies increases only slightly, from about -29 db in iteration 9 to -27 db in iteration 14, the diagrams clearly show a smoothing out of the previously "craggy" terrain between them. The monopolization of these six frequencies increases until iteration 15, at which point we see various other small patches of frequencies begin to get louder.

At this point something rather unexpected begins to occur: a "disruption phase" in which the heretofore established "resonant frequencies of the room" suddenly begin, not to reinforce themselves, but to waver and topple. Notice, for example, two very subtle yet portentous differences in the spectral content of iterations 14 and 15: the sudden appearance of a small bump at 260 Hz and the unexpected increase in the previously diminishing bump just below 400 Hz. While these two details are certainly not sonically significant (they are surely inaudible fluctuations within the context of the rest of the sound) they are significant in that they appear to be anomalous to the established trend. Up to this point in the piece, frequencies have either been consistently increasing or decreasing in amplitude.

As we scan over the diagrams of the the next several iterations (15-22 or so) we see a sudden influx of frequency content, a dramatic return of the "cragginess" of iterations 8-10. Where in iteration 15 there was no frequency content at all above 500 Hz, in iteration 21 there are three major peaks. The same is true of the low frequency content (compare the few hair-thin strands below 200 Hz in iteration 16 with the sizable spikes that they become in iteration 21). Where did all of the sound come from? What caused this relatively sudden and dramatic rupture when up to this point the analysis was conveniently reinforcing our assumptions of how things would play out? It appears that starting around iteration 15, some threshold was reached. These six "false resonances" who, by whatever acoustic coincidence fortuitously gained prominence, could not maintain. It is a classic example of the so-called tipping point, in which some previously unseen instability, pushed to the limit by the increasing combinational incompatibilities of the primary resonances, leads to a catastrophic paradigm shift.

The disruption phase eventually gives way to a new set of dominant frequencies beginning at about iteration 22. It is notable that none of these new frequencies (102 Hz, 223 Hz, 262 Hz, 303 Hz, 534 Hz, and 655 Hz) are identical to (or really even that close to) the last set. This second emergence phase lasts all the way to the end of the piece. A significant increase in the overall peak amplitude level also occurs in this phase, reaching its highest level in the entire piece (-35 db) at around iteration 29. By the last iteration of the piece, we can see that, compared to the culmination of the first emergent phase in iteration 14, the apparent stability of these new frequency bands is striking. The six peaks all have clearly defined center points, nice smooth sloping sides, and there are only a few trifling frequency bumps around 350-450 Hz to challenge their dominance. It seems safe to assume that had Lucier continued the process for another 32 iterations these six frequencies would be reinforced and narrowed down ever further and further until all that was left was a droning hexachord of sine tones. However, as this analysis has shown, feedback networks are innately unstable. Are these six frequencies really the *true* resonant frequencies of the room, or is their emergence merely fortuitous. And why, we might ask, did the tiny little bump at 460 Hz suddenly get bigger in the last iteration after consistently decreasing for ten preceding iterations?

The figures on pages 102-103 chart the amplitude levels of the two sets of dominant resonant frequencies over the course of the entire piece. The two charts combined clearly demonstrate the four-part structure proposed. In the first chart, we see a dramatic increase in the amplitudes of several of the first set of dominant frequencies at around iteration 9 (some of them start earlier). In iteration 17 there is a nose-dive descent resulting from the disruption that began a few iterations earlier. Chart 2 shows that the rise of the second set of dominant frequencies becomes clear starting at iteration 23 (leaving a 6-7 iteration "gap" between the decline of the first set and the rise of the second, correlating to the disruption phase). The sudden dip in amplitudes of four of the six peak frequencies in iteration 31 reveals some instabilities in this "final" resonant structure. Astoundingly, five of the six final peaks are within 2 Hz of an equal-tempered pitch (the lowest peak at 104 Hz is still only 6 Hz below A2). Several harmonic relationships exist: two pairs of octaves (104-220 Hz [stretched] and 262-523 Hz), two minor thirds (220-262 Hz and 262-311 Hz), and a major third (523-657 Hz). In musical terms, the final chord of the piece is an A minor add #11 chord (a-a-c-d#-c-e).

Rhythmic Analysis

Lucier hypothesizes in the text of *I am sitting in a room* that any semblance of his speech will be destroyed, "with perhaps the exception of rhythm." Once again, digital sound analysis software allows us to determine precisely the accuracy of his hypothesis. The charts on pages 104-106 show the amplitude levels over time for iterations 1, 8, 16, 24 and 32 of the phrase, "I am sitting in a room." By focusing on a relatively short excerpt and observing precise fluctuations in the amplitude levels of the excerpt across the span of the piece, we can reach conclusions about how the feedback process affects local-level rhythmic structures in general.

The first iteration shows three amplitude peaks corresponding to the inherent linguistic stresses in the phrase, "I am sitting in a room." The word "I" corresponds to the first amplitude peak at -15.2 db at 0.2 seconds. The phoneme "si" from the word "sitting" corresponds to the second amplitude peak at -17.4 db at 0.6 seconds. The phoneme "oo" from "room" corresponds to the third amplitude peak at -18.5 db at 0.9 seconds. Thus, at a tempo of quarter-note equals 150, the resulting rhythm of the first iteration of "I am sitting in a room" is:  (with the last note fading out for an inexact duration).

Peak locations only describe part of the rhythmic character of a sound. Equally important is the attack—the speed of the amplitude increase before the peak. The faster the amplitude increase, the more clearly one will perceive the peak as a bona fide rhythmic division. Of course, the threshold at which we will perceive peak amplitudes as being "rhythmic" is highly subjective and most likely differs greatly between listeners. For the purposes of this analysis, we will consider an amplitude peak that is preceded by an amplitude increase of an average of at least one decibel per 100 milliseconds to be a rhythmic division. The *intensity* of the rhythmic division can be derived from the same calculation (i.e. the second rhythmic attack in the first iteration of "I am sitting in a room" has a rhythmic intensity of 5.6 because the amplitude increases from -23 db to 17.4 db over the course of the 100 milliseconds leading up to the peak).

Moving on to the eighth iteration of "I am sitting in a room," the first thing we notice is a dramatic increase in overall amplitude. However, this does not concern our rhythmic analysis as we are only interested in speed and intensity of the rhythmic figures. Iteration 8 is unique among our selected excerpts in that there are four clear rhythmic divisions (all of the others have three). It appears that a new, clearly perceivable peak amplitude has appeared after the last peak of the first iteration (the resonance of the open vowel sound "oo" in room has accumulated to create an echoing amplitude surge). If we assign a rhythm based on the amplitude peaks at .4, .9, 1.2 and 1.4 seconds, we get: 

In the 16th iteration the second peak (corresponding to "si" from "sitting") has been sufficiently smoothed out to prevent a clearly audible rhythmic division. All that we can hear now are the diluted pulses that are the remants of "I" and "oo," followed by the latter's reverberant echo. The peaks now are spread even farther apart and the intensities have decreased to their lowest levels. The (barely) perceivable rhythmic figure is: 

In the 24th iteration we find an unexpected reversal in the preceding trend. The overall amplitude level drops significantly, the intensity of the amplitude peaks is much stronger, and we see the reappearance of the second rhythmic division ("si-") and the disappearance of the last rhythmic division (the echo of "-oo-"). The rhythmic divisions, in other words, are faster and clearer. The rhythm can be notated as: 

Finally, in the last iteration of the phrase, we see an overall amplitude that nearly flatlines at around -10 db. We can only just make out the three original amplitude peaks at "I," "si-," and "-oo-." The distance from the first to the second peak has increased by 100 milliseconds and the distance from the second to the third peak has increased by 200 milliseconds since the 24th iteration. Thus, the final rhythm of the piece, if it can even be considered perceivable, is: 

What conclusions can be drawn from the preceding observations? Besides determining that the rhythmic content of the piece, while not entirely destroyed, is certainly altered, the data also shows a direct correlation between rhythm and the overall diversity and stability of the frequency content. The following chart shows the location and intensities of the amplitude peaks of the selected iterations:

	.1"	.2"	.3"	.4"	.5"	.6"	.7"	.8"	.9"	1"	1.1"	1.2"	1.3"
Iteration 1	x				5.6			5.2					
Iteration 8	x					1.5			4.1		2.8		
Iteration 16	x									2.5			1.9
Iteration 24	x						3.4				1.8		
Iteration 32	x							1					1.5

The chart shows a clear pattern of rhythmic elongation, or "temporal spreading"[7] coupled with a decreasing intensity through several of the iterations. This process seems to "reset" to an earlier stage in its evolution somewhere between the 16th and 24th iteration. The rhythmic analysis corresponds precisely with the frequency analysis, which clearly showed that the 16th iteration was the culmination of the "first emergent phase." We can recall that the subsequent instability in the spectrum was followed first by a period of increased frequency diversity and fluctuation and then by the gradual

[7] Blesser and Salter, *Spaces Speak*, 134.

reemergence of a new set of primary resonant frequencies (iterations 22-32). The figure above shows a corresponding reappearance of the pattern of increasingly long and soft rhythms in iterations 24 and 32. Thus, the strength and stability of the frequency spectrum is proportional to the amount of temporal spreading (duration between perceived rhythmic events) and inversely proportional to the amplitude variance (perceived rhythmic intensity) of the sound.

The quasi-unpredictable ebb and flow of *I am sitting in a room* is both scientifically verifiable and aurally perceivable. Lucier himself makes note of this fascinating quality of the work: "The rate of transformation isn't constant either. It seems to operate on its own set of rules. It's very mysterious."[8] Of course, there is no real "mystery" to what happens in the piece, just an incalculably complex network of physical interactions governed by a few simple rules. It is pure sonic emergence. Like an ant hill or stock market, it unfolds without design into an unforeseen structure of elegant complexity.

[8] Lucier, *Reflections*, 102.

Chapter 8: Mathematical Feedback Systems in Music

The previous two chapters dealt exclusively with acoustic feedback systems in music. In acoustic feedback, the feedback loop is a physical (though not tangible) process. Sympathetic resonance and electronic circuitry affect matter directly, whether it be air pressure or electrical current. In mathematical feedback systems the loops are a step removed from the resulting sounds. Mathematical feedback systems typically generate streams of data that the composer then applies to some musical parameter or set of parameters. This data "translation" is often fundamentally arbitrary (in the sense that the recursive algorithm that is employed has no direct ontological connection to the parameter to which it is applied). Data may be implemented either through traditional musical notation for instrumental music or computer programming for electroacoustic music. In the case of electroacoustic music, where the processing typically occurs out of sight, the difference between Tudor-esque "no-input" electronic feedback (discussed in the following chapter) and computer-generated mathematical feedback systems may be difficult to discern. Nevertheless, the division between data-flow and signal-flow is quite clear and typically results in radically different-sounding music.

Mathematical feedback systems are a subset of a larger and more historically established branch of music known as algorithmic music. All algorithmic music operates primarily according to a set of prescribed rules—often (but not necessarily) mathematical in nature—which drive the evolution of various parameters of the composition. Mathematical feedback music operates in precisely this way, with the added contingency that the mathematical rules are recursive. In a mathematical feedback system the resulting data from a mathematical equation is reinserted into the very same equation that produced it.

Since no electronic gadgetry (or even electricity) is required to produce mathematical feedback music, there are a few historic precedents for this type of music. The ancient technique of isorhythm, which dates back to the 14th century, is a quasi-recursive musical system. In isorhythmic music the pitch material (color) and rhythmic material (talea) are fixed and metrically unaligned. Depending on which element (pitch or rhythm) is considered "foundational," the other element is essentially fed-back recursively with each rotation, yielding a finite number of variations on the material.

Another famous historical example of mathematical feedback is Bach's *Canon per tonos* from *The Musical Offering*, shown below.

This brief passage, like many of the canons in *The Musical Offering*, is meant to be repeated for an unspecified number of times. What is striking about this example, however, is that the passage modulates up a whole step midway through (from C minor to D minor), making a direct repeat musically illogical. What is instead intended is that with each repetition the performer should transpose the pitches up a whole step, resulting in a continuously rising cycle. *Canon per tonos* is therefore a perfect example of a single-node invariable loop. The material is "processed" (modulated up a step) and reinserted (repeat sign) ad infinitum. While Medieval isorhythm and *Canon per tonos* are probably not the only historical precursors to recursive algorithmic composition, they could probably be correctly described as historical curiosities in this regard. They represent a tendency toward a more scientific construction of music which all but disappeared for several hundred years henceforth. The remainder of this chapter will investigate a few of the ways that 20th-century composers (including myself) have found to employ recursive algorithms in their music.

Rational Melodies

The music of Tom Johnson, more than that of any other composer, represents the extremes of efficiency with which mathematical algorithms can be applied to composition. Johnson is an outspoken critic of so-called "intuitive" or "emotional" narratives in music, which he characterizes as "autobiography." He has stated that he wants to, "*find* the music, not compose it."[1] For Johnson, this desire for musical discovery, rather than expression, leads him toward the application of mathematical algorithms, and, in the following examples, *recursive* mathematical algorithms.

Rational Melodies is a set of 21 monophonic pieces for unspecified instrumentation. Each melody is a musical translation of a numerical sequence, pattern or formula. The extreme rhythmic consistency, symmetrical scale structures (often alternations of two types of intervals), and complete lack of expressive, dynamics or

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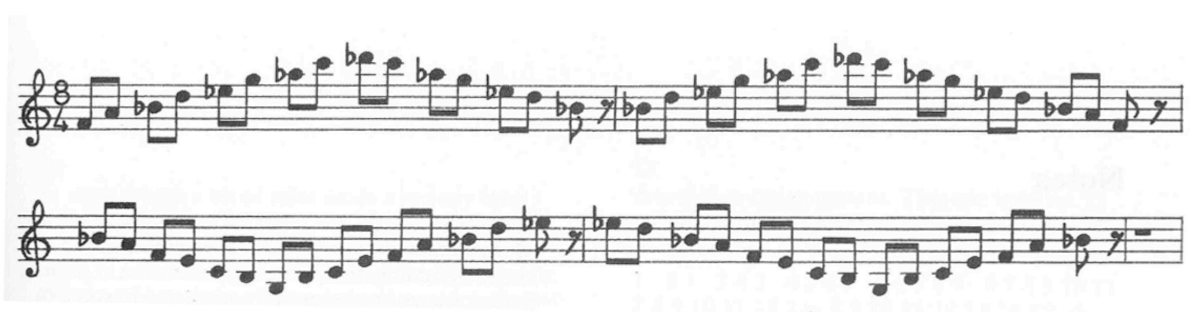
[1] Tom Johnson, *The Chord Catalogue* (New York: XI, 1999). CD.

articulation markings all serve to heighten the "rationality" of the mathematical system at work. While all of the pieces in the set are algorithmic in nature, not all of them are technically recursive. Many of the melodies are based on simple mathematical sequences, or what Johnson calls "counting patterns." *Rational Melody III*, for example, can described in digits as: 1 12 123 1234 12345 2345 345 45 5 51 512 5123 51234 1234 234 34 4 45 ... 23451 3451 451 51 1. These counting patterns provide an illustrative example of the extent to which we can find recursive behaviors in even the most mundane situations. Whole number counting, for example, is essentially an invariable single-node network in which the number 1 is added recursively to a starting integer.

Two pieces in the set are particularly notable in their use of mathematical feedback systems. *Rational Melody XXI*, the last piece in the set, employs a quasi-12-tone compositional technique. As Tom Johnson explains in the performance notes, "The second bar is the retrograde of the first bar. The third bar is the inversion of the second bar (by scale degrees, not by exact intervals). The fourth bar is the retrograde of the third bar."[2] The first four phrases of the piece are provided here:



[2] Tom Johnson, *Rational Melodies* (Paris: Editions 75, 1990).

Depending on the starting material, this simple process of recursively applying alternating transformations of inversions and retrogrades can generate a substantial amount of new material. Johnson, typically exhaustive in the application of his algorithmic processes, only applies these three transformations. The subsequent phrases are simply a repetition of this material with one fewer note each time. In addition, the decision to use scale degree inversion rather than intervallic inversion severely limits the amount of variation that will occur. A hypothetical application of this process to a 12-tone row using exact intervallic inversion generates significantly more pitch material (exactly how much depends on the row). Take, for example a given 12-tone row in which the first note is C and the last note is C# (the internal order of the row is irrelevant). If we apply Johnson's process of alternating retrogrades and inversions starting with row P0, we get the following 24 distinct rows before the cycle repeats itself:

P_0 - R_0 - RI_2 - I_2 - P_2 - R_2 - RI_4 - I_4 - P_4 - R_4 - RI_6 - I_6 - P_6 - R_6 - RI_8 - I_8 - P_8 - R_8 - RI_{10} - I_{10} - P_{10} - R_{10} - RI_0 - I_0 - (P_0)

The same result (although in a different order) occurs from rows in which the interval of the first and last notes is a perfect fourth (or its inversion, a perfect fifth). Other row types in which the interval of the first and last note is a more symmetrical division of the octave yield less variation. A whole step or a major third will generate 12 distinct rows, a minor third will generate 8 rows, and a tritone will generate only 4. The type of music produced by the generative algorithm used in *Rational Melody XXI* is highly dependent on the initial input. Where another composer might have used the same algorithmic means to produce a drastically more varied and dissonant work, Johnson has subtly tailored his material to suit his quasi-tonal, minimalist aesthetic.

Rational Melody XVI employs a somewhat more obscure and sophisticated method of mathematical feedback. It is one of a few "doubling processes" that occur in the set, which consist of a few rules used for inserting new notes between a pair of existing notes. Johnson explains the process: "In this case we begin arbitrarily with the scale degrees 1-2-1 and proceed by examining each pair of notes. If they are adjacent we insert the next highest scale degree, and if they are not adjacent, we insert the scale degree that falls between the pair."[3] The numerical result of the first 5 "levels" of the process is as follows:

1																2																1
1								3								2								3								1
1				2				3				4				2				4				3				2				1
1		3		2		4		3		5		4		3		2		3		4		5		3		4		2		3		1
1	2	3	4	2	3	4	5	3	4	5	6	4	5	3	4	2	4	3	5	4	6	5	4	3	5	4	3	2	4	3	2	1

The piece consists of the first seven levels of the process presented in reverse order. As Johnson points out, "several curious things occur as side effects of this logic." We can see that each level is a palindrome that introduces a new scale degree one step higher than the preceding row (the new note always appearing near the middle of the row). These general characteristics seem to be latent reflections of the original 1-2-1 sequence (a palindrome with a peak in the middle). However, each level also yields an increasing amount of complexity and unpredictability that seems to display emergent behavioral trends.

The first phrase of the piece (corresponding to the seventh level of the doubling process) is 129 notes long. A high degree of internal structure is immediately perceivable within the phrase. Page 107 of the appendix shows the phrase with

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[3] Johnson, *Rational Melodies*.

bracketed structural divisions and melodic sequences. The phrase can be broken down into a four-part structure of A B B' A', of which the last two are the retrograde of the first two. The first section extends from the beginning until the end of measure 6 and consists of three iterations of a two-measure sequence that ascends by step. The two-measure sequence is itself composed of three iterations of a two-beat sequence that ascends by step. This ascending sequence of ascending sequences displays a sophisticated fractal-like self-similarity that emerges without the aid of any intentional "top down" compositional decisions.

The second section is much shorter, consisting of measures 7 and 8, and also displays self-similar attributes. This section consists of two iterations of a one-measure sequence that descends by step. Once again each iteration itself contains a two-note sequence that descends by step (D-F-C-D-A-C). The self-similarity is also apparent between the sections, as the one-measure sequence beginning at measure 7 is essentially the second half of the two-measure sequence at the beginning (ascending four-note scale, leap down, step up, leap down, step up). All of the preceding material appears in retrograde starting at measure 9. Thus, the structure of the phrase up to that point is presented in inversion: two iterations of a one-measure ascending sequence of ascending sequences followed by three iterations of a two-measure descending sequence of descending sequences.

While we can certainly observe and reliably predict global patterns in *Rational Melody XVI*, the local level behavior of the melody operates seemingly with a mind of its own. Granted, like all of the *Rational Melodies*, the piece carries the emotional weight of a Hanon piano exercise. "Composers," as Johnson says, "are usually more interested in inspiration, intuition, feelings, self-expression."[4] The achievement of the piece is its ability to create expansive and complex structures that reveal clearly perceivable patterns from an almost negligible amount of starting material.

R = 4, then 3.5

A few years ago I was asked to compose some music to accompany an experimental short film by my friend Sarah Carlson. The film, entitled *Lines*, consisted entirely of a continual and rapidly moving close-up shot of the ground. The camera movements tracked the various "lines" made by cracks, paint, sticks, and other incidental miscellanea, moving from one trajectory to another. The result is an experience that is simultaneously wildly disorienting and hypnotically fluid. My goal in creating the music for the film was to achieve a similar kind of sensation through sound. I wanted to create an immediate sense of chaos that, like the film, revealed hidden patterns of elegant simplicity over time.

The first thing that came to mind when I began thinking along these lines was James Gleick's book *Chaos*, which I had read several years ago and had been thinking about ever since. The book charts the history of the various mathematical discoveries that eventually came together under the banner of chaos theory. Chaos theory is the study of certain dynamic systems, both mathematical and physical, that, despite being governed by deterministic equations, appear to behave randomly. Naturally occurring examples include fluid dynamics, weather patterns, orbiting satellites, and population fluctuations. Of most interest to me in the context of this project was the idea—

[4] Johnson, *Rational Melodies*.

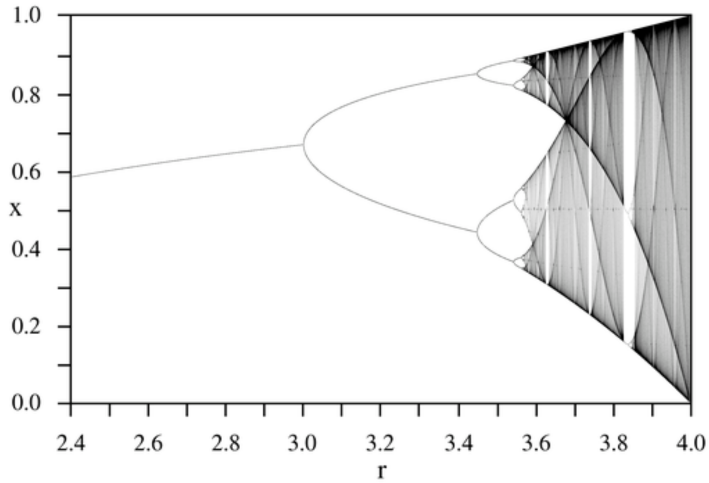
commonly referred to as "the butterfly effect"—of dynamic systems with a high degree of sensitivity to initial conditions. This seemed to be the central tenet of Sarah's film, that microscopic factors such as the way a leaf had fallen or the direction a cigarette butt was pointing have potentially huge effects on the direction of the film.

To create the music I made use of a particular chaotic equation that I found in the book that displays this quality of high-sensitivity to initial conditions. The equation mimics the fluctuations of the population growth of a species in a hypothetical, isolated ecosystem. A commonly used example is foxes and rabbits: the population of the foxes is dependent on the ratio of rabbits (food) to foxes (mouths). Too many foxes will eat too many rabbits, leaving not enough food for the next generation (if they eat all of the rabbits both species will become extinct). However, the subsequent decrease in fox population will in turn provide a temporarily relatively safe environment in which the rabbit population can replenish. This naturally-occurring example of a negative feedback system will often, over time, reach an equilibrium state in which both the fox and rabbit populations will stabilize at mutually beneficial levels (although the rabbits might take issue with this characterization). The following recursive equation achieves a remarkable simulation of such a dynamic system:

$$x_{(n+1)} = r \cdot x_{(n)} \cdot (1-x_{(n)})$$

This equation requires only two values to get it started: an initial starting population ($x_{(n)}$) and a rate of growth (r). The population value in the equation is always between 0 and 1 and can be thought of as a percentage of capacity. A population value of 1.0 will subsequently lead to a population value of 0, or extinction, in the next generation. The rate of growth (r) acts as the "driving factor" of the equation, metaphorically representing the rate of reproduction of the species. Given a starting population and a rate of growth the equation yields a numerical value representing the population of the next generation ($x_{(n+1)}$). This value—the value of the population of the second generation—is then fed back into the equation, producing the value of the population of the third generation. This recursive process continues on indefinitely, charting the ebb and flow of the population levels over many generations.

Mathematicians discovered that an unexpected thing occurs as a result of the changing value of r. When the rate of growth is below a certain level (specifically, 3) the population levels over several generations will stabilize at a single value (this is not surprising as homeostasis is a typical result of negative feedback systems). However, if the rate of growth is increased slightly above this value a bifurcation occurs, wherein two levels of stasis occur between alternating generations. For example, a growth rate of 3.2 will result in alternating population levels of approximately .513 and .799. If the growth rate is increased still more to just below 3.5, yet another bifurcation occurs resulting in a stable and repeating pattern of four distinct population levels. These bifurcations occur at exponentially smaller intervals until a theoretically infinite number of bifurcations results in so-called chaotic behavior. The following diagram charts the evolution of the equation as the growth rate increases past the point of chaos. The bifurcations are clearly visible.



The piece I eventually composed and that was used in Sarah's film is titled *R = 4, then 3.5* (the meaning of which is now obvious). The recursive formula described above was used as the generating agent for the pitch material in the piece. The numerical values for population over time are directly translated into the frequency (Hz) values of sine tones.[5] Percentage values were simply scaled between the frequency range of my preference. In order to most clearly communicate the subtleties of the system I articulated the frequency values using pure sine-tones with a bell-like amplitude envelope (a sharp attack followed by a gradual decay) at a consistent tempo of 70 notes per minute. As the title implies, the first section of the piece uses values with a growth rate of 4 and the second section uses values with a growth rate of 3.5. I felt this structure created a satisfying cadence to the piece as the final four pitches gradually converge on their respective destination frequencies.

The chart on the following page shows the frequency values for the first 30 pitches of each of the two sections. A careful analysis of the data reveals subtle

[5] The piece actually consists of several layers of sound and structure, including a randomized collage of street sounds extracted from the original film recording. For the purposes of this paper, however, we will restrict discussion to the particular aspect that uses mathematical feedback as its generative method.

behavioral patterns that become immediately perceivable when articulated with sound. For example, when r = 4, rather than producing a random sequence of numbers (as one might expect), various tendencies emerge. The first one is a kind of "gravitational pull" that occurs close to zero and a repulsive force that occurs near 1. This is most obvious if we look at generations 13-20. In generation 13 the population skyrockets to a near-extinction level of .999. This plummets in the next generation to .001, after which it gradually (and then exponentially) begins to rise. Another apparent emergent behavior is a centrifugal force surrounding the value .75. As it turns out, an exact population value of .75 in the equation will result in a subsequent value of .75, resulting in complete equilibrium. This point of equilibrium acts as an attractor, pulling in values that get close to it (the closer the value, the stronger the attraction). This behavior is apparent in generations 20-25 (values: .73, .787, .67, .885, .409, .967). The values surround the value of .75, each generation seeming to overcompensate more and more, propelled by a growth rate beyond the limits of stability.

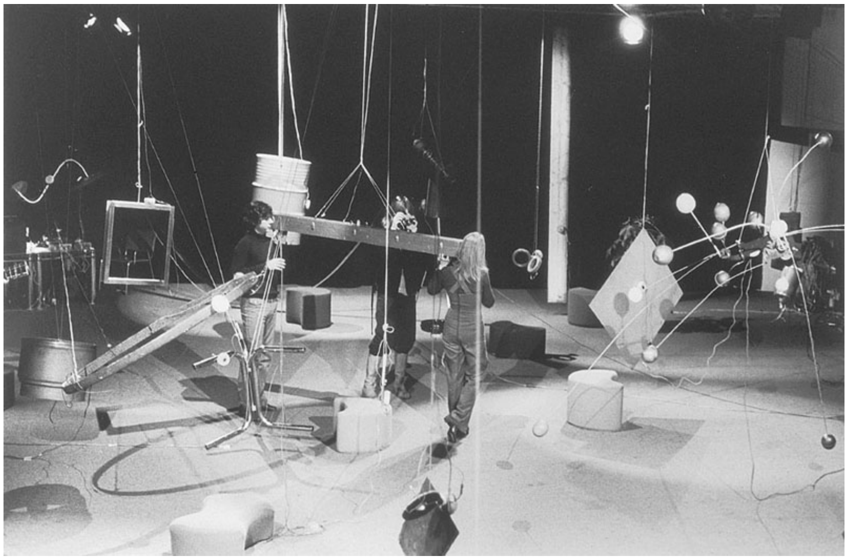
The behavior patterns when r = 3.5, though less theoretically interesting, turned out to be surprisingly compelling to listen to. The second section of the piece is essentially a gradual process of a four-note microtonal chord tuning itself. Besides being an engaging activity of following the evolution of the chord to its unforeseen final structure, I found that the unintended (though certainly not unpredictable) presence of acoustic beating created a compelling additional level of "acoustic chaos" to the piece.

Chapter 9: David Tudor and "No-Input" Feedback Systems

In the 1940's and 50's, David Tudor gained a reputation as the foremost interpreter of experimental and avant-garde piano music. His virtuosic premieres of such landmark pieces as Pierre Boulez's *Piano Sonata No. 2* (1950) and John Cage's *Music of Changes* (1951) cemented his legacy in the history books and, for a while at least, eclipsed his own equally significant compositional achievements. Unbeknownst to many, Tudor dedicated himself exclusively to composition following his retirement from performance in the early 1960s. His cumulative output from 1964 (the date of *Fluorescent Light*, his first acknowledged composition) until his death in 1996 includes over 60 works, primarily for live electronics and sound installations. Unfortunately, due to his compositional methodology, neither scores nor recordings exist for many of his pieces. Thanks to a small handful of recordings and a new generation of dedicatees, an overdue resurgence of interest in Tudor's music seems to be underway.

Tudor's most famous and regularly-performed composition is undoubtedly *Rainforest*, a piece that began in 1968 and gradually evolved over the next eight years into four distinct versions (*Rainforest I-IV*). *Rainforest* is a variable sound installation in which participants select or build various musical "sculptures" to which electronic transducers are attached (the photograph below shows a setup for a performance of *Rainforest IV* from 1973; a young Paul De Marinis is on the left).

Though none of the *Rainforest* installations incorporate feedback explicitly (each "speaker" is simply fed a looped recording of the participant's choosing), the project clearly reflects an early interest in pseudo-biological acoustical ecosystems. To a



certain degree, of course, the resonance of a particular object in *Rainforest* will be affected by the resonances of others, and this does induce a more subtle element of feedback into the work. By Tudor's own admission, however, the disembodied structure of the installation did not allow for a significant feedback effect: "I did experiment several times .... where I did get feedback into the system. But that isn't so interesting when the output is so small; it gets very interesting when they're larger."[1]

As effective and influential as *Rainforest* turned out to be, Tudor expresses some dissatisfaction with the arbitrariness and occasional inappropriateness of the source materials. Tudor somewhat sarcastically hypothesized that, "You can give a tango party and play tango through all of these instruments and one after the other and it would be glorious, I can guarantee you. But it is not going to be my piece."[2] His subsequent compositional efforts attempted to address this perceived shortcoming while retaining the complex networked structures of the *Rainforest* series. The answer came in 1972

[1] David Tudor, "An Interview with David Tudor by John David Fulleman," *EMF*, http://www.emf.org/tudor/Articles/fullemann.html.

[2] David Tudor, "Interview with David Tudor," EMF, http://www.emf.org/tudor/Articles/rogalsky_inter1.html.

when Tudor discovered that, when compiled correctly (or incorrectly as the case may be), electrical components such as mixing boards, effects pedals, and equalizers will spontaneously create sound without the aid of any external input. Tudor describes the process of the discovery in an interview with Teddy Hultberg:

> Rather than think of tone generators or recordings of natural sounds etc., I experimented with principles of amplification, trying to make amplifiers oscillate in an absolutely unpredictable manner. In the end, it turned out that I didn't even need any amplifiers because most electronic equipment uses the principle of amplification. You need filters, modulators and mixing equipment which have gain stages. By piling these components up, I was able to work without any sound generators and I made several pieces in that manner.

Untitled

The first piece that Tudor realized with this newly discovered technique of "no-input feedback" was called *Untitled* (1972) and was composed to accompany a reading by John Cage of his *Mesostics re Merce Cunningham*. By his own account, the final design for the piece was close to unmanageable, both in terms of physical setup and performance. There were approximately sixty electronic components involved (mostly "home-brew," as he describes them, including amplifiers, attenuators, filters, and modulators) each with its own assortment of knobs and switches. A massive arsenal of cables was required to connect all of the components.[3] In addition, all of this gear was to be performed by just one person, Tudor himself. Considering the astronomical number of potential signal paths in the piece, any attempt at controlling such an instrument must have seemed an almost comically Herculean task.

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[3] In his later years, Tudor frequently travelled to performances of his works with an entire suitcase dedicated solely to cables.

As it turns out, *Untitled* did in fact turn out to be unmanageable, and Tudor had to resort to performing the piece with the safety net of prerecorded material. As he explains, "it was not that it was too complicated, it was simply too difficult. I mean, after all, feedback is feedback. And even though I'm good at isolating the output, in the end there is always the possibility that it will take off."[4,5] While the immensity and complexity of the setup allowed for a huge amount of sonic and behavioral variety, it also prevented Tudor from having the controlling influence that he required to steer the piece in the direction he wanted. In order to reconcile these two considerations, Tudor was forced to develop an entirely new performance practice, one in which the cause-and-effect relationships between bodily motions and the resulting sounds must have been disarmingly nebulous when compared to his lifelong training as a pianist. Those that witnessed the later-period performances of his live electronic works claim that his virtuosity as a performer of feedback surpassed even his legendary abilities as a pianist.[6]

As Tudor experimented more and more with his network of electrical components, his understanding and manipulation of the behaviors of no-input feedback became increasingly sophisticated. Specifically, Tudor began to focus much of his attention on a technique that he termed "phase shift oscillation." As we discussed at the end of chapter 3, feedback resonance is determined by both the gain level and phase alignment of a particular frequency (the Barkhausen stability criterion). By controlling

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[4] John D.S. Adams, "Giant Oscillations," *Musicworks* 69 (1997).

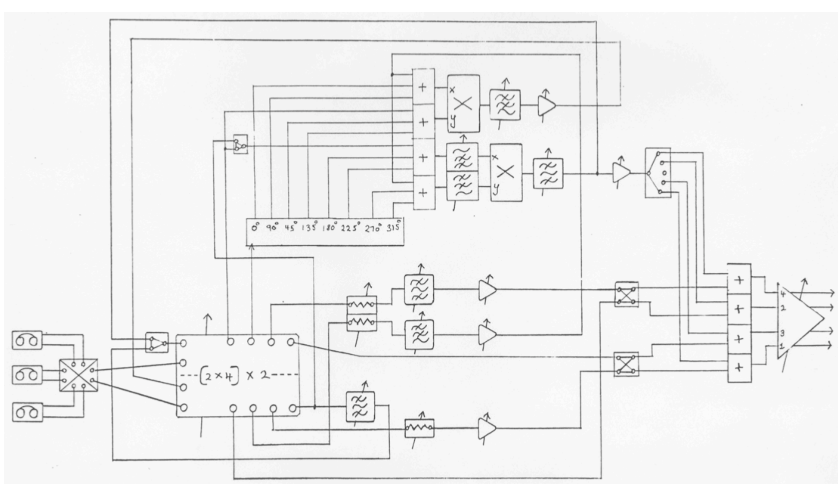
[5] Tudor was eventually able to conquer the challenge of a completely live no-input feedback performance in 1975 with *Toneburst*. Sadly, there is no commercially available recording of this work, which by several eye-witness accounts is Tudor's masterpiece.

[6] David Tudor, *Neural Synthesis* (New York: Lovely Music, 1995). CD.

and altering the phase relationships of the components within his setup, Tudor was able to gain greater access to the nuance of the sounds that were coming out. As composer and Tudor collaborator John D.S. Adams explains in his article *Giant Oscillations*:

> Phase shift oscillation is a variation of feedback oscillation where the audio signal that is fed back to the input is altered by between zero and 360 degrees of phase. As his work progressed Tudor discovered that the oscillation he was achieving wasn't only about feeding back resonant (but otherwise non oscillating) circuits, it was also the specific configuration of these circuits and how they were allowed to share with each other, their instabilities.

Since potential feedback frequencies are determined by phase alignments, a rapid and continuous alteration of the phase relationships of the various resonating circuits will dramatically increase the instability of the system. This condition of stable instability is the holy grail of live electronic feedback; it is the point at which the instrument seems to become "alive." In Tudor's words, it is, "the point where I know the composition is finished .... where the composition is alive, and it doesn't need any more...culture."[7]



Schematic for *Untitled* (showing several instances of outputs returning to their own inputs)

[7] David Tudor, "David Tudor and Larry Austin: A Conversation," *EMF*, http://www.emf.org/tudor/Articles/austin.html.

Neural Synthesis Nos. 1-9

In the last five years of his life David Tudor worked exclusively on the *Neural Synthesis* series, a set of live electronic feedback compositions of a more complex design than anything he had previously attempted. By the late 1980s, Tudor's live stage setup had expanded to its rational limit in terms of size and complexity. As a potential new path forward in his work with feedback, Tudor began work on a computer-based synthesizer that would be able to incorporate even more potential signal connections within a single portable unit. The project evolved into a three year collaboration with computer engineers Forrest Warthman and Mark Holler, who had been working on similar ideas outside of the musical context. According to Warthman, "Mark was introducing a new analog neural-network microchip whose design he had recently managed. The chip electronically emulates neuron cells in our brains and can process many analog signals in parallel."[8]

Neural networks and complexity theory had become an increasing focus of computer engineering at this time. Neuroscientists, mathematicians, anthropologists, and computer engineers were striving to understand and, if possible, to *simulate* the processes of the most complex feedback network of all: the human brain. The unified project would eventually become known as A.I.—or artificial intelligence—and would dramatically influence numerous diverse disciplines, including medicine, communication technology, entertainment, advertising, and national security to name just a few. The concept of artificial intelligence in Tudor's music is all but explicit in discussions of his

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[8] Tudor, *Neural Synthesis*.

own music: "Electronic components and circuitry, observed as individuals and unique rather than as servo-mechanisms, more and more reveal their personalities."[9]

The Neural Network Synthesizer differed from Tudor's previous approach to feedback composition in that instead of using separate electrical components strung together with patch cables, the signal flow and "gain stages" would now be contained on Holler's chip. Warthman describes the basic mechanics of the synthesizer in the liner notes of the Neural Synthesis recording:

> The neural-network chip forms the heart of the synthesizer. It consists of 64 non-linear amplifiers (the electronic neurons on the chip) with 10240 programmable connections. Any input signal can be connected to any neuron, the output of which can be fed back to any input via on-chip or off-chip paths, each with variable connection strength. Near the onset of oscillation the neurons are sensitive to inherent thermal noise produced by random motions of electron groups moving through the monolithic silicon lattice. This thermal noise adds unpredictability to the synthesizer's outputs, something David found especially appealing.[10]

Though a complete technical understanding of the synthesizer is admittedly beyond my current capability, it seems clear that it is operating with fundamentally the same principles as Tudor's early experiments with mixing boards and effects pedals. At its core, the synthesizer consists of an interconnected network of amplifiers with variable amplitude and frequency controls with which Tudor performs the music. One rather significant advantage in the neural synthesizer was the ability to rapidly reconnect the feedback pathways during the performance itself (this would have required awkwardly unplugging and replugging dozens of audio cables in Tudor's previous setups).

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9 Adams, "Giant Oscillations."

10 Tudor, *Neural Synthesis*.

The *Neural Synthesis* pieces were originally composed for two musicians using a 16-channel sound system. Tudor created both binaural and stereo recordings of several performances on the Neural Synthesizer by overlaying (multitracking) two edited takes. Tudor describes the recording process as an essential compositional step in the creation of the *Neural* pieces, as opposed to an arbitrary "sampling" of one improvised performance: "It is the sum, the overlaying of the successive performances, which establishes and defines the compositional process. Because these recorded performances were approached as a compositional process, this is also how they need to be listened to."[11] Thus, Tudor's work brings us back to our earlier discussion in Chapter 1 regarding improvisation and indeterminacy. In both *Untitled* and *Neural Synthesis*, the indeterminacy results from a self-inflicted incapacitation brought on by the unmanageable complexity of the network. Paradoxically, Tudor seems to resist this indeterminacy by constantly struggling to promoting his aesthetic, both during the performance and the recording/editing process. As Tudor succinctly puts it, "I put myself into the most difficult and complex situation and try to get out of it."[12]

Conclusions

The music of David Tudor serves as an appropriate stopping and summation point for the varieties of musical feedback that have been discussed in this paper. His music, more than any other, incorporates many of the mathematical, acoustic and conceptual characteristics that have drawn composers to work with feedback in the first

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[11] Tudor, *Neural Synthesis*.

[12] David Tudor, "An Interview with David Tudor by Teddy Hultberg," *EMF*, http://www.emf.org/tudor/Articles/hultberg.html.

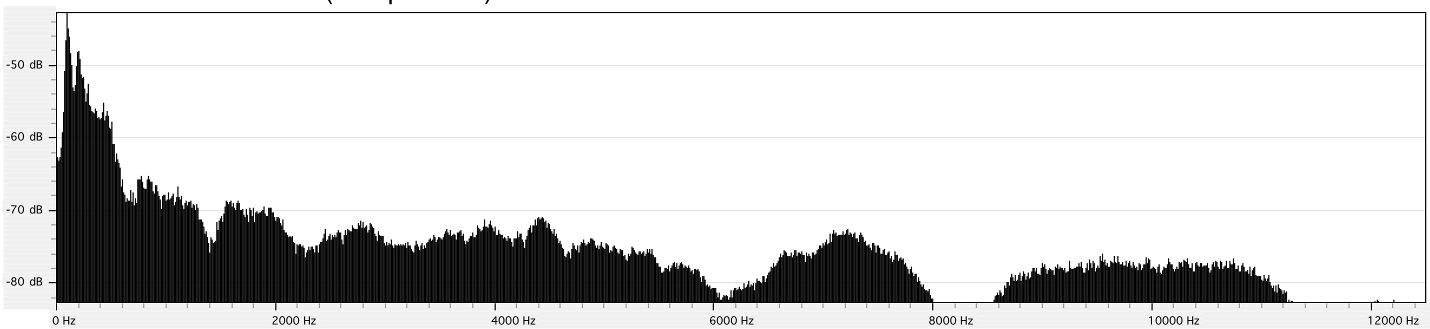
place. It reflects the sympathetic resonance of acoustic feedback, the evolutionary dynamics of mathematical systems, and, occasionally, the uncompromising brutality of pure noise. More than anything else, Tudor's music demonstrates the capacity for playful discovery that so many composers have found in feedback. Hearing him speak, it seems that the increasing complexity in his networks was driven more by a childlike curiosity than any kind of sophisticated academic pursuit (though it is surely a mixture of both).

The composers and techniques discussed in this dissertation represent only a small fraction of those relevant to the use of feedback in music. Many composers have found ways of incorporating the mechanics of feedback systems in less direct ways. Christian Wolff's game pieces, for example, in which performers react to each other according to a predetermined set of limitations, are an excellent example of a social feedback system in music. Another example is Stockhausen's *Solo for Melody Instrument with Feedback* (1969) in which three feedback "assistants" record the soloist and play back altered fragments in an aleatoric fashion. Many more methods of incorporating feedback systems in music are surely conceivable, and, as we have seen, the musical results can be anything but narrow. From the sedate scale-studies of Tom Johnson's *Rational Melodies* to the hypnotic droning of Alvin Lucier's *I am sitting in a room* to David Tudor's deafeningly wild electronic improvisations, feedback as a technique is hardly a one-trick pony. Its range and versatility prohibits a predictability of result that sometimes accompanies compositional systems. As a compositional technique, feedback elegantly intersects the three opposing 20th-century strategies of control, chaos, and intuition. It presents a precarious and delicate situation, in which minute deviations can have major impacts, and vice versa. In the words of David Tudor, "Well, when you realize that things don't always turn out the way you think, I mean, there's one thing that happens: you started off working in a certain direction and it leads you somewhere else."[13]

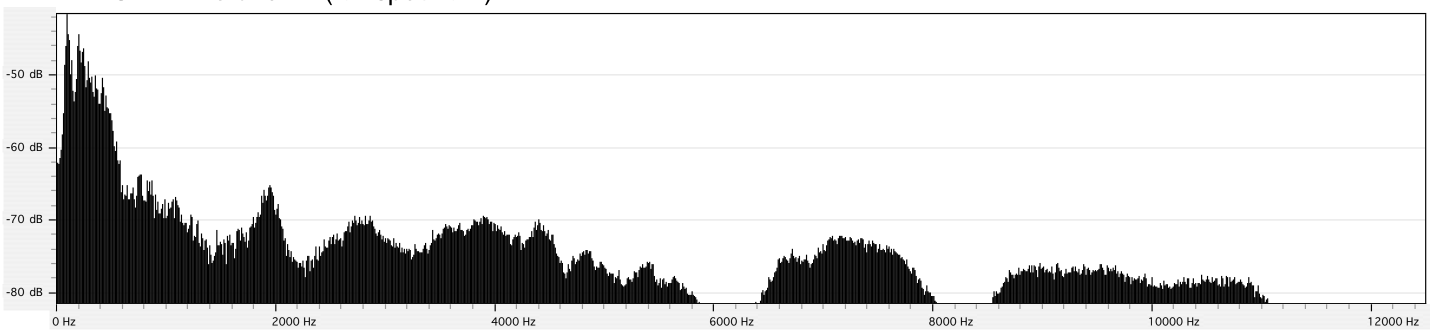
[13] Tudor, interviewed by Fulleman.

APPENDIX

IASIAR - Iteration 1 (full spectrum)



IASIAR - Iteration 2 (full spectrum)



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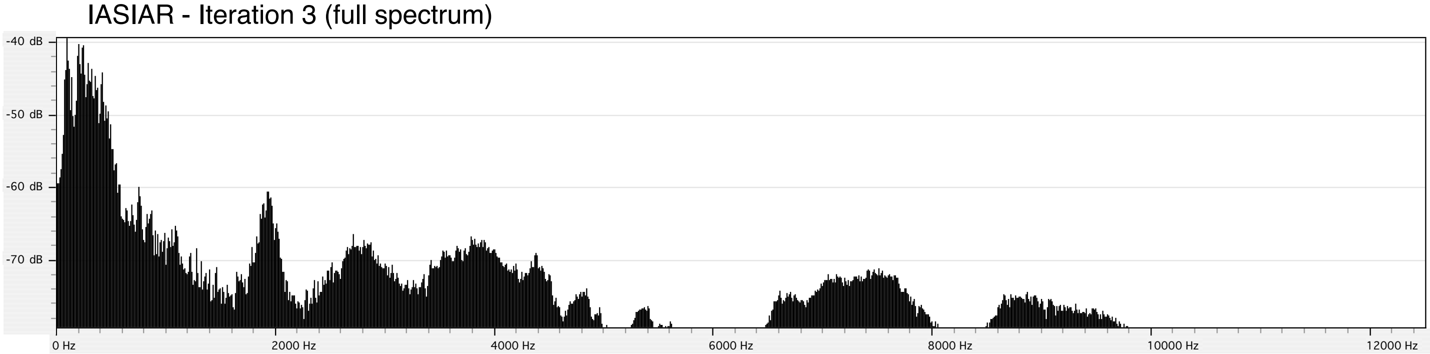

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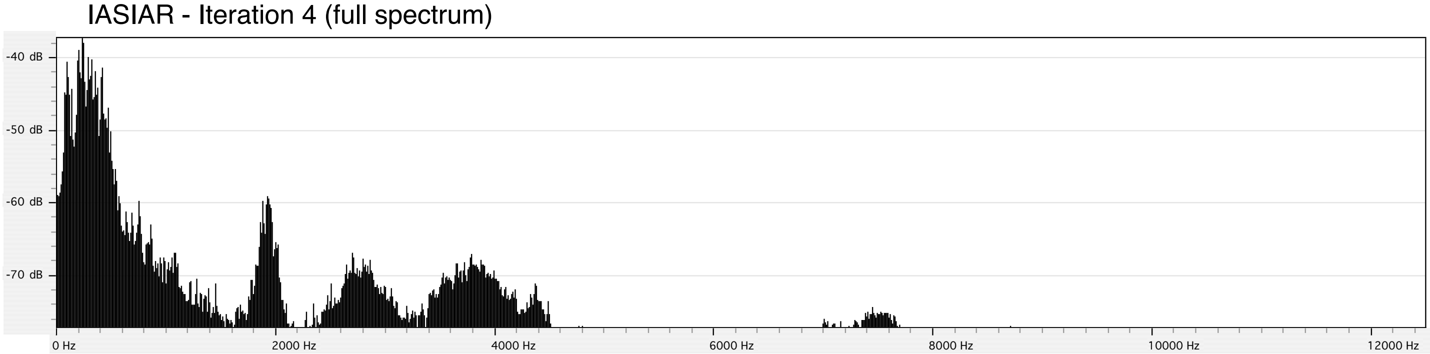

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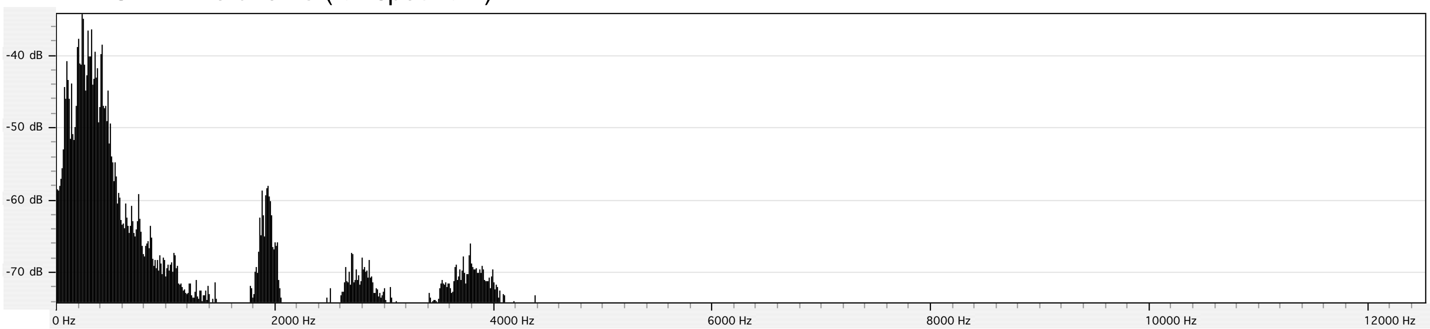

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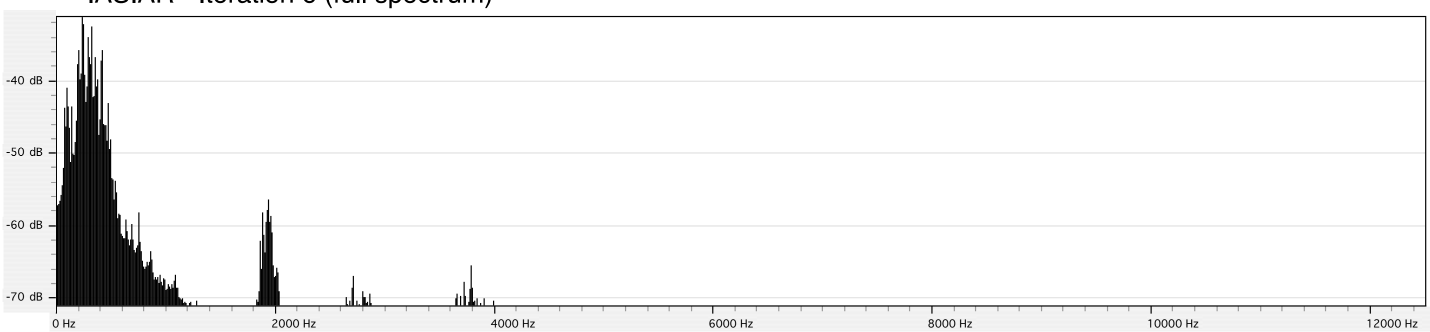

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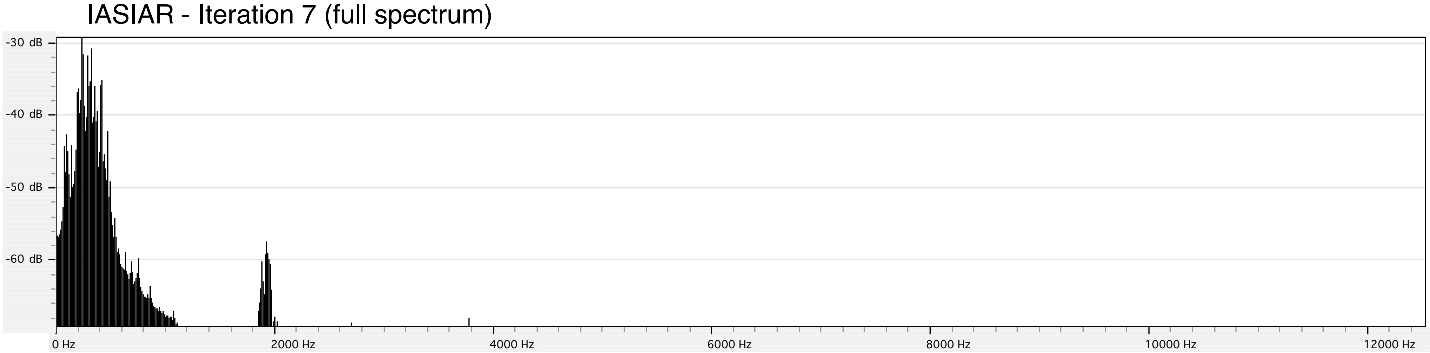

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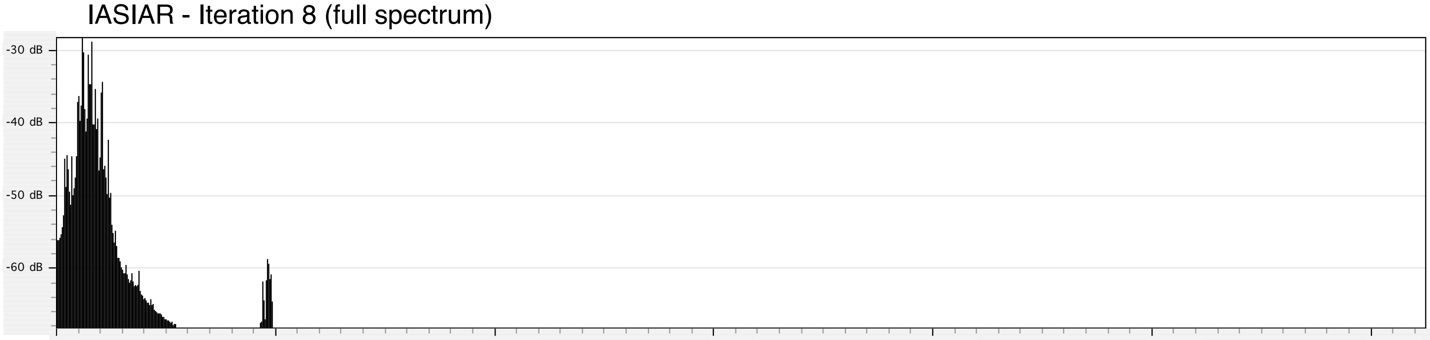

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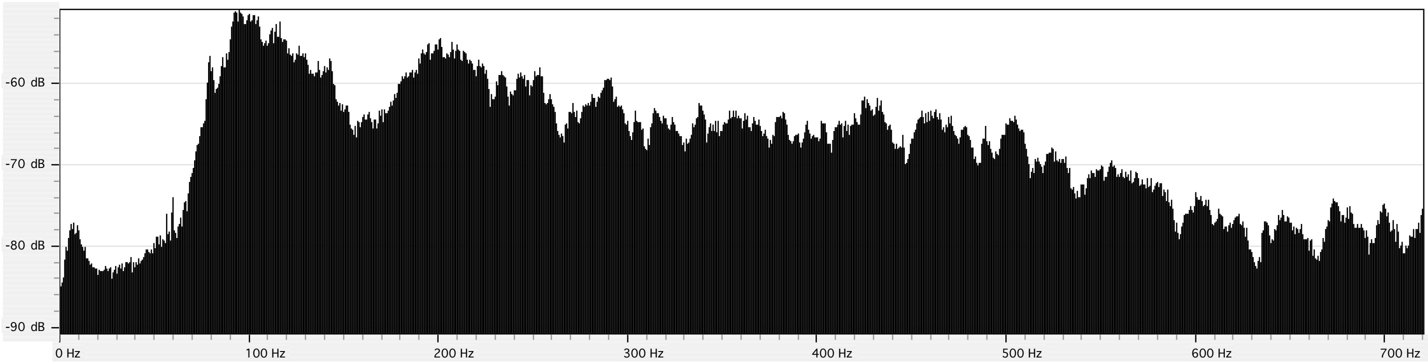

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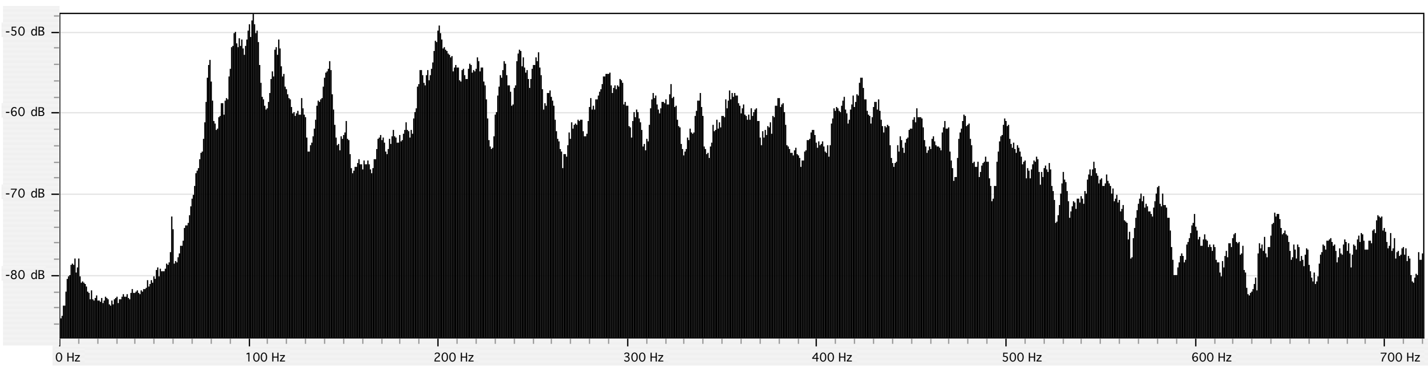

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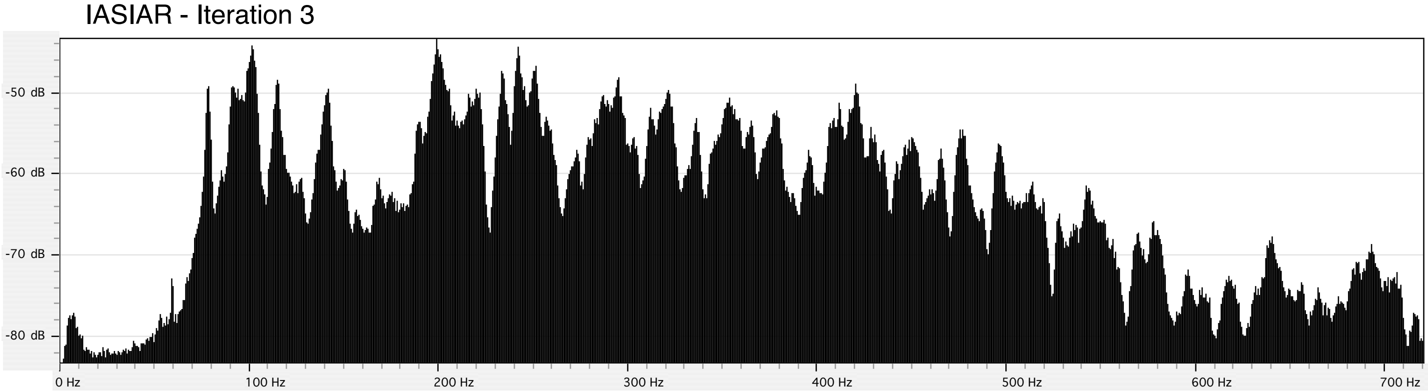

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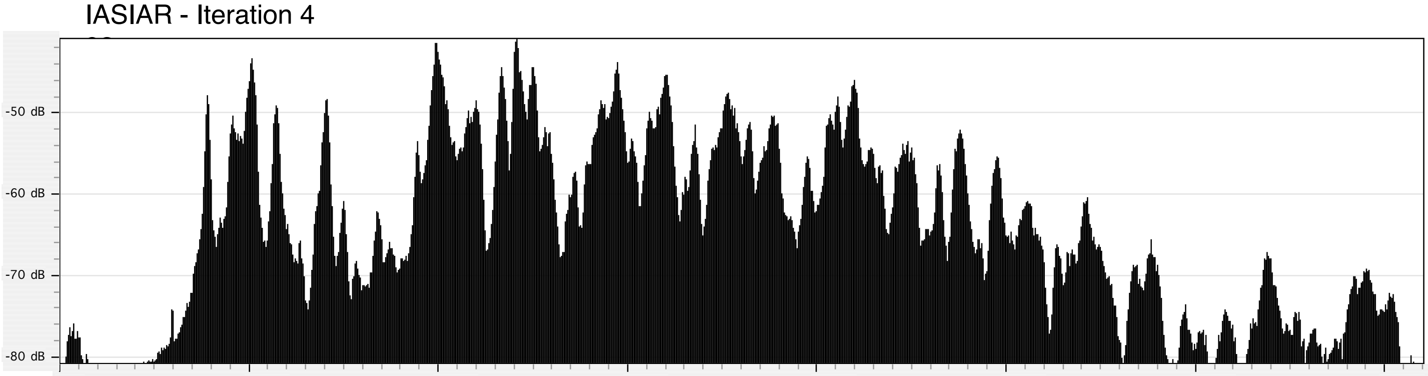

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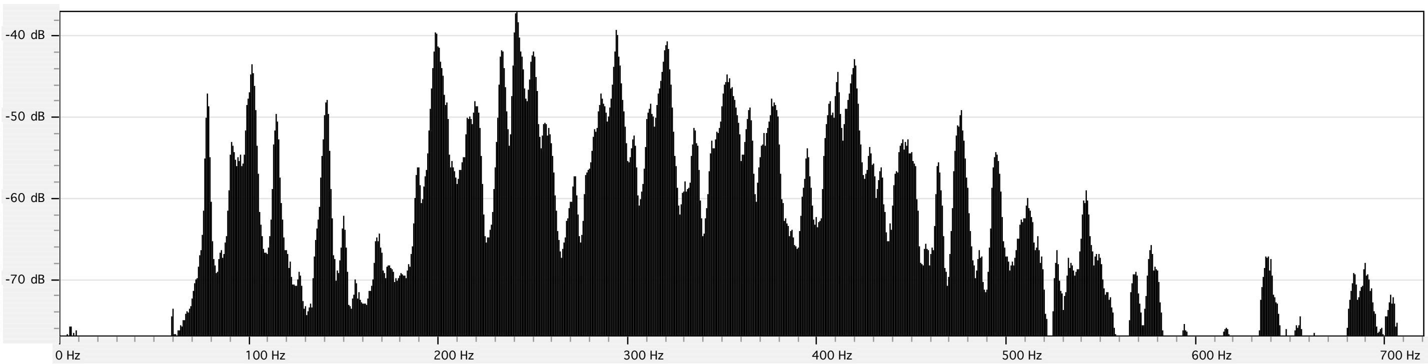

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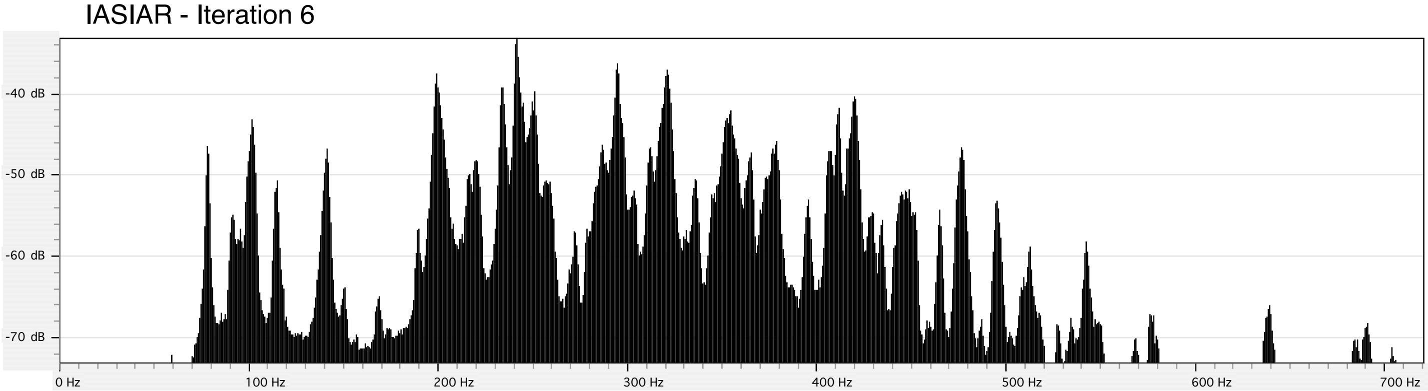

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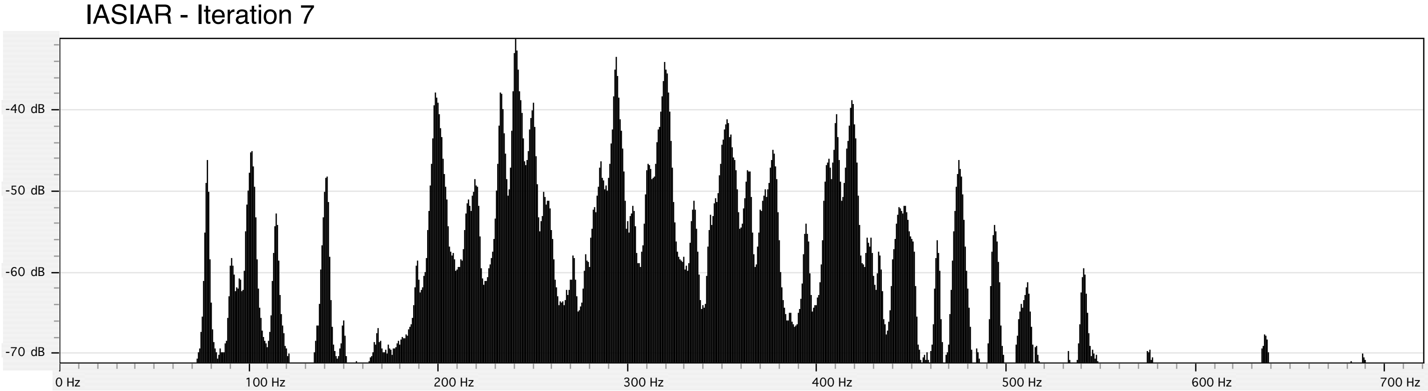

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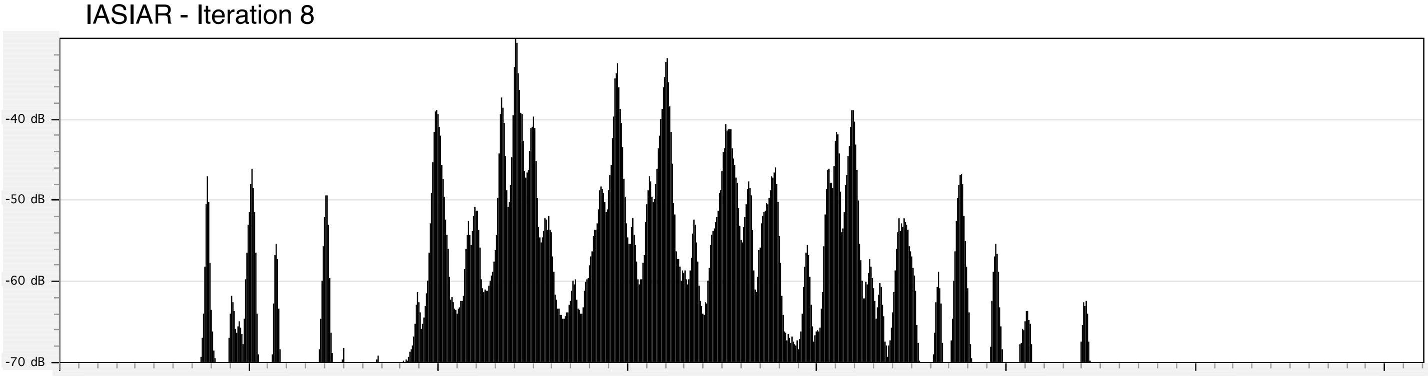

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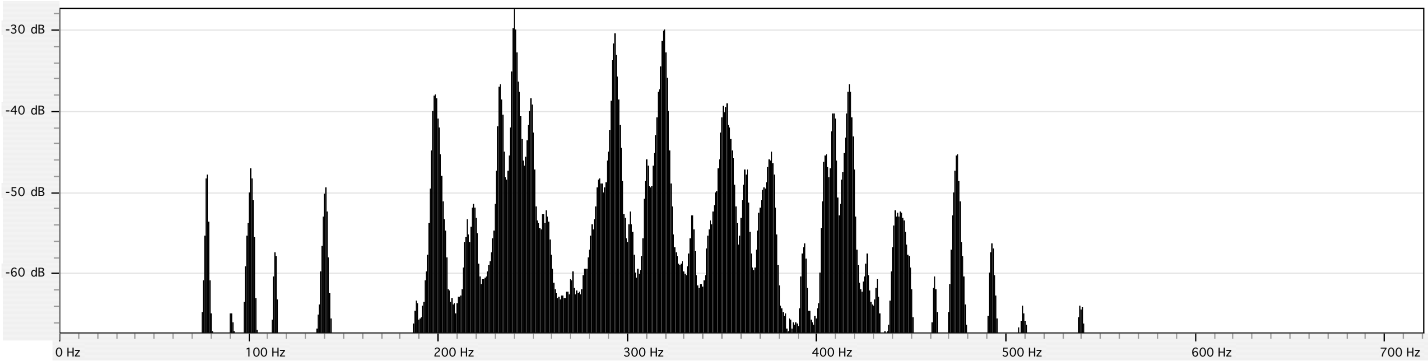

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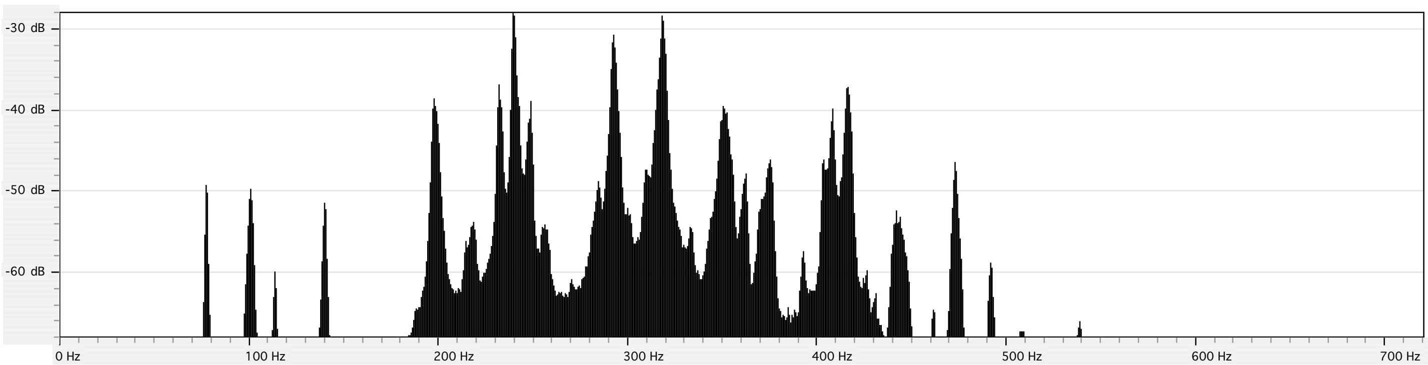

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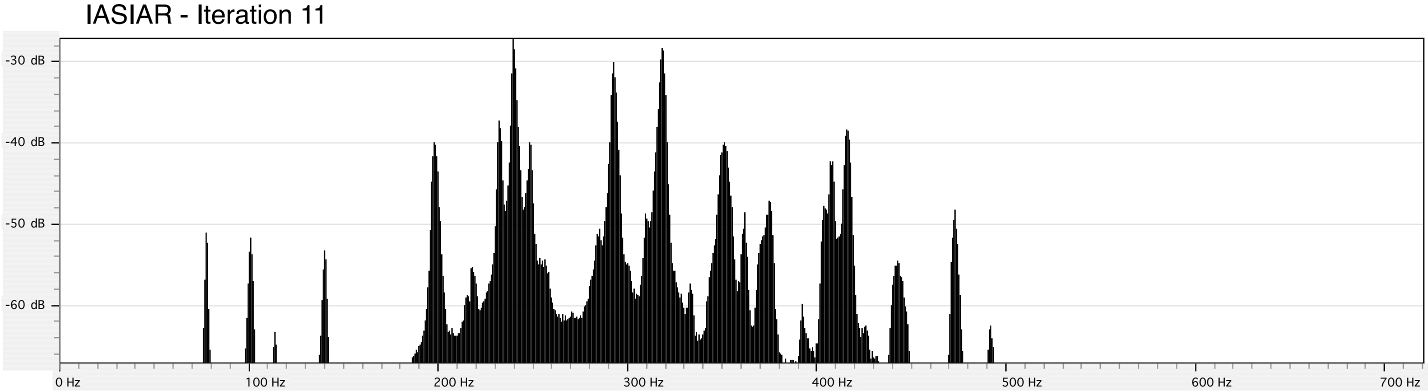

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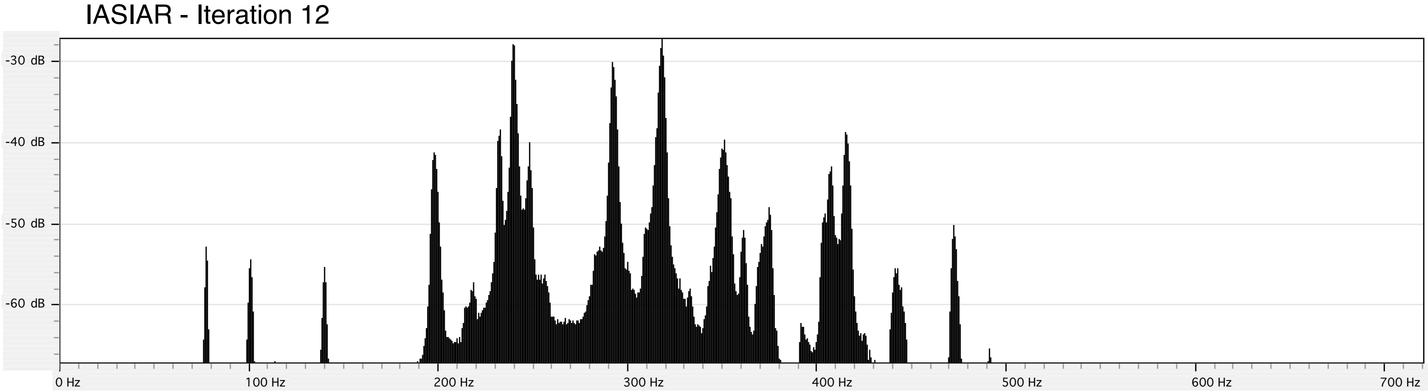

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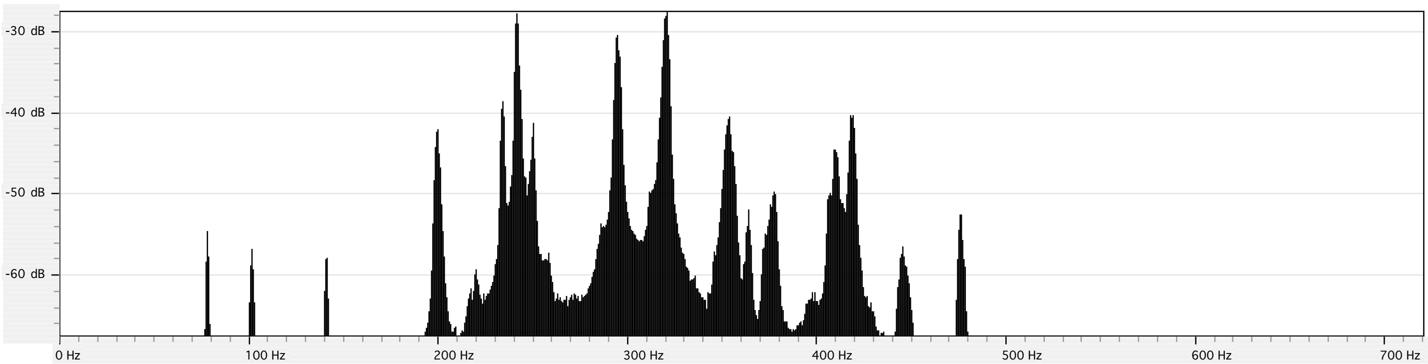

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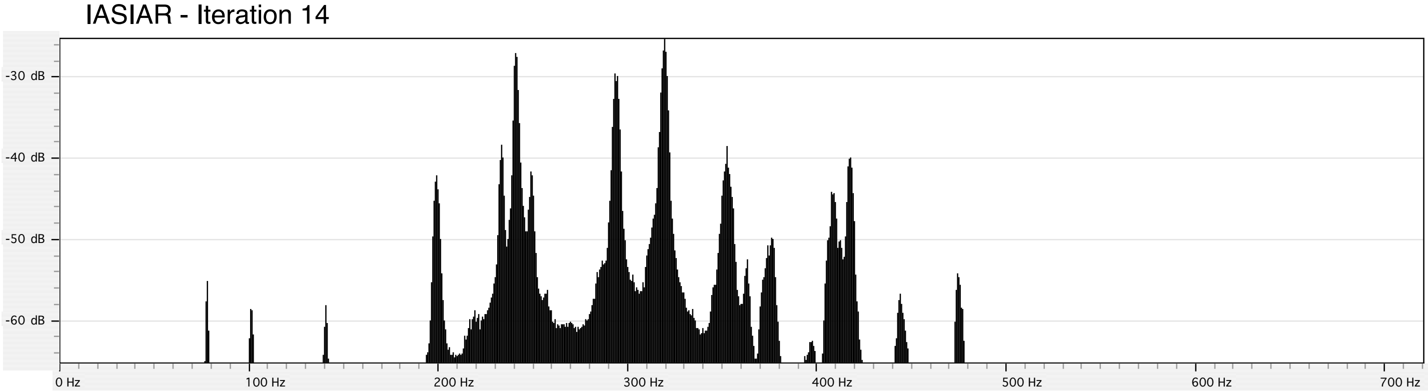

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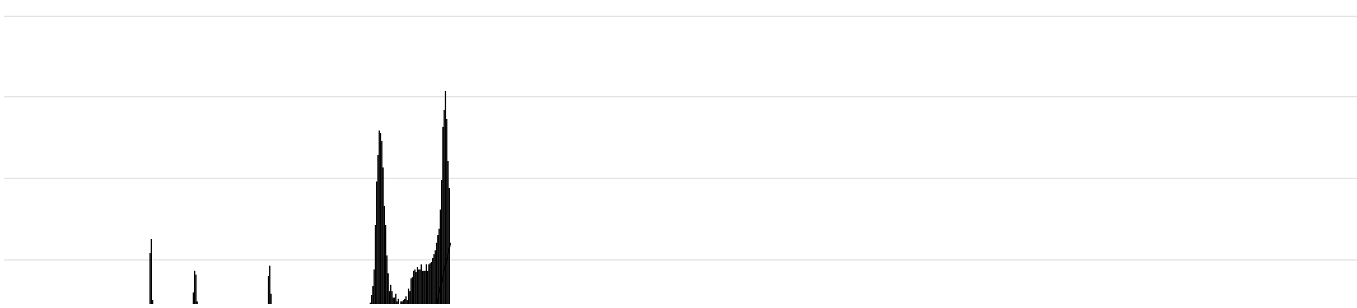

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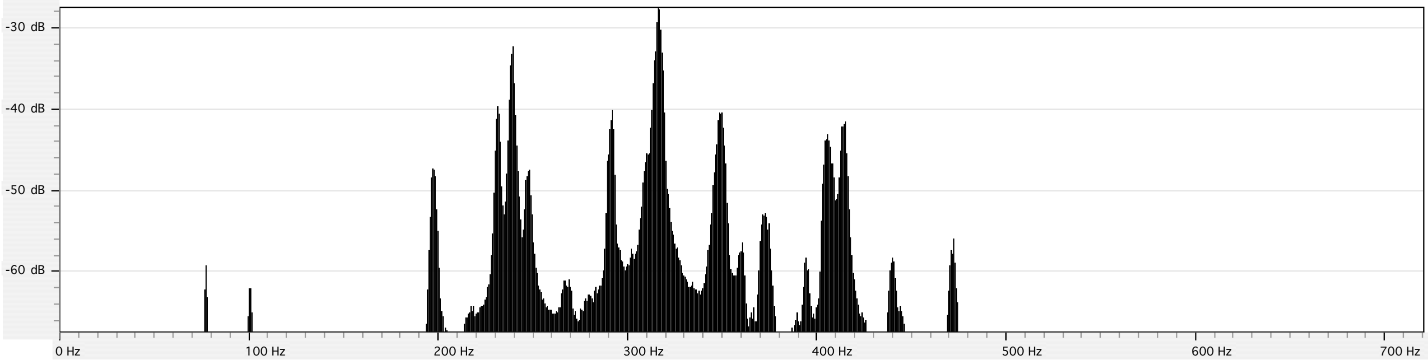
IASIAR - Iteration 17



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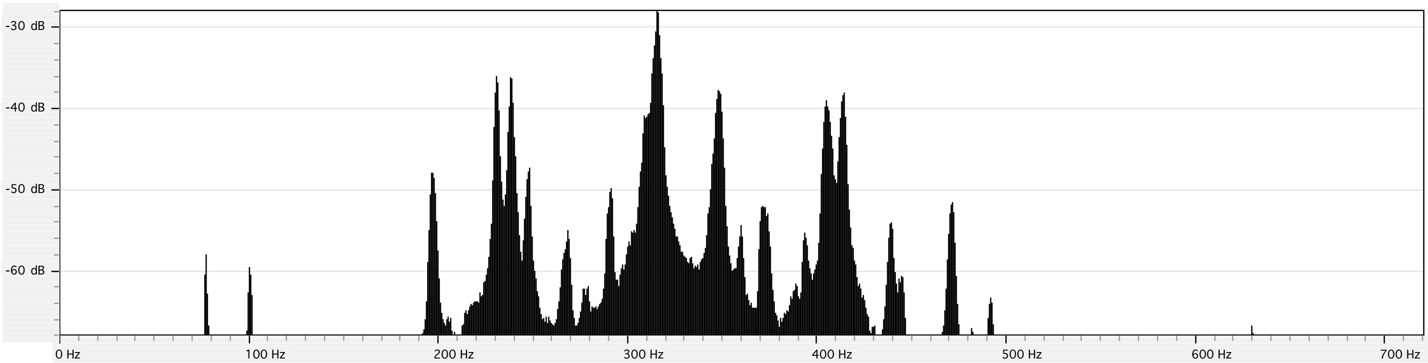

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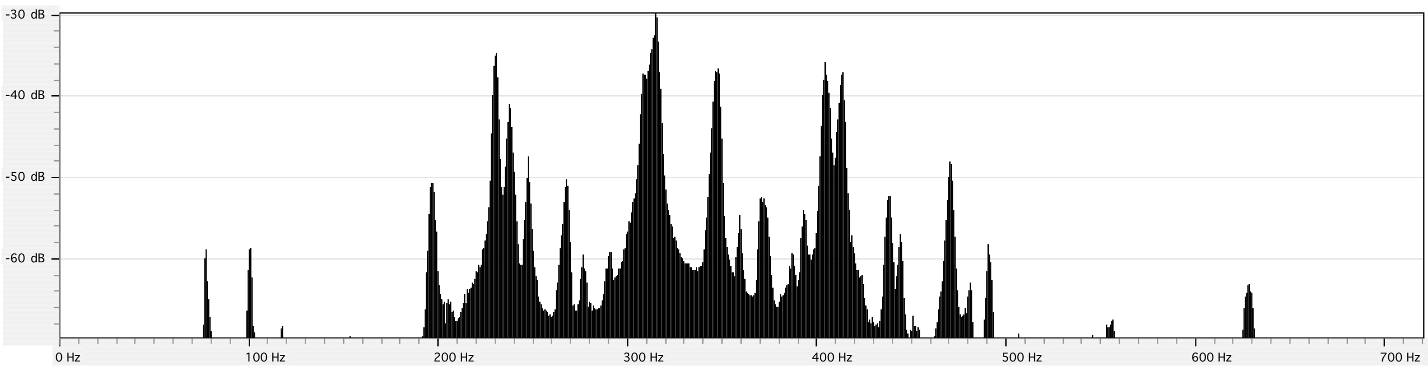

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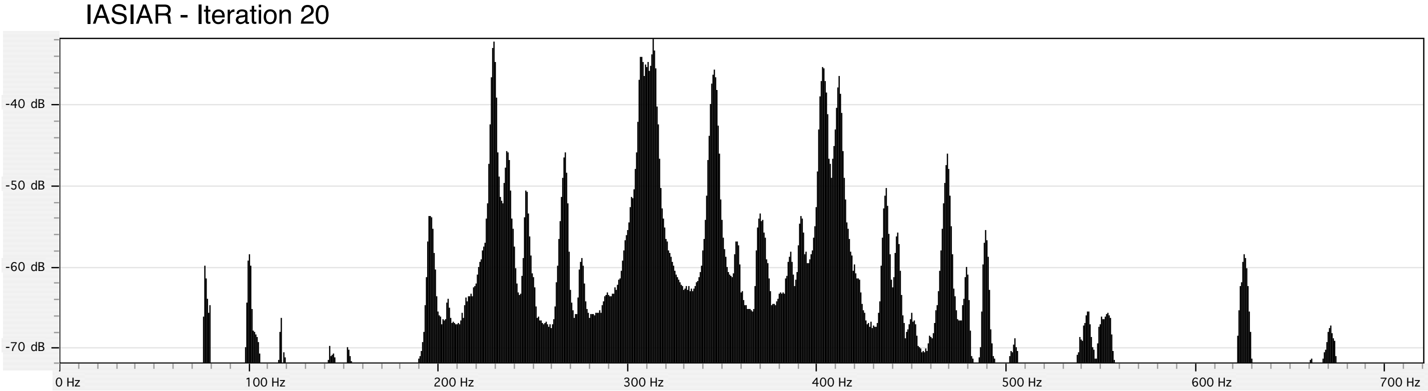

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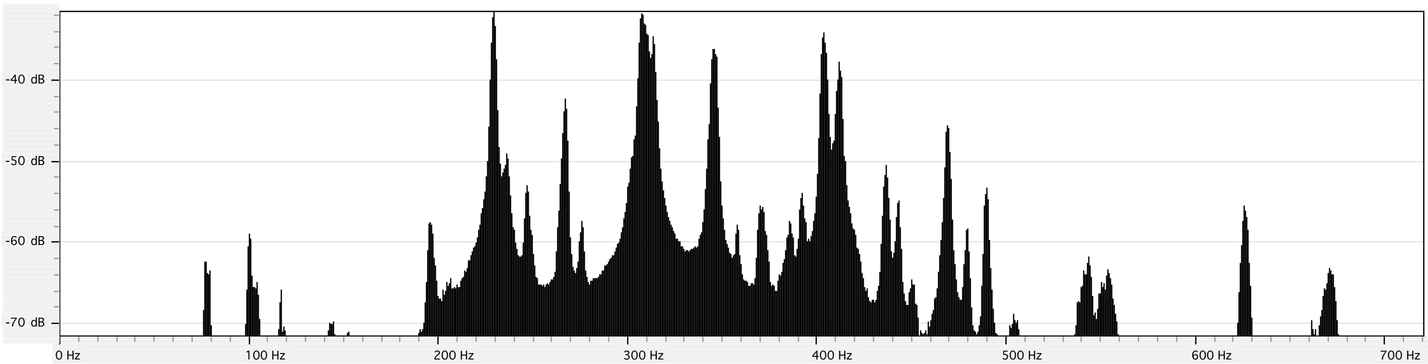

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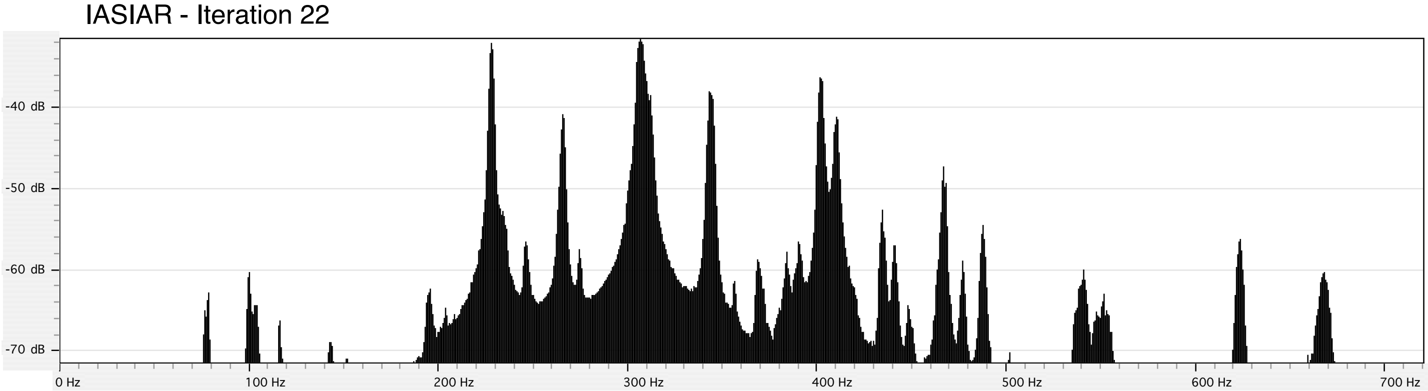

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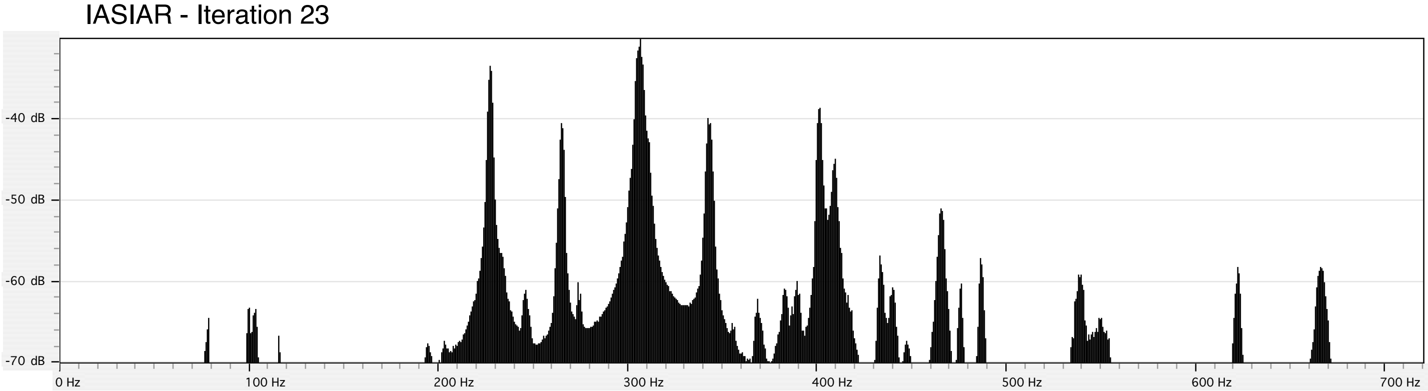

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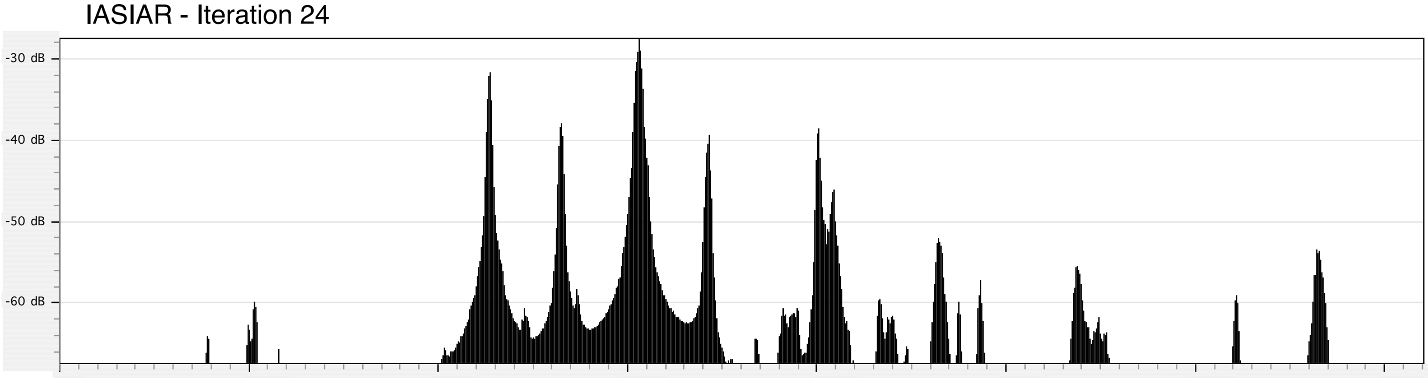

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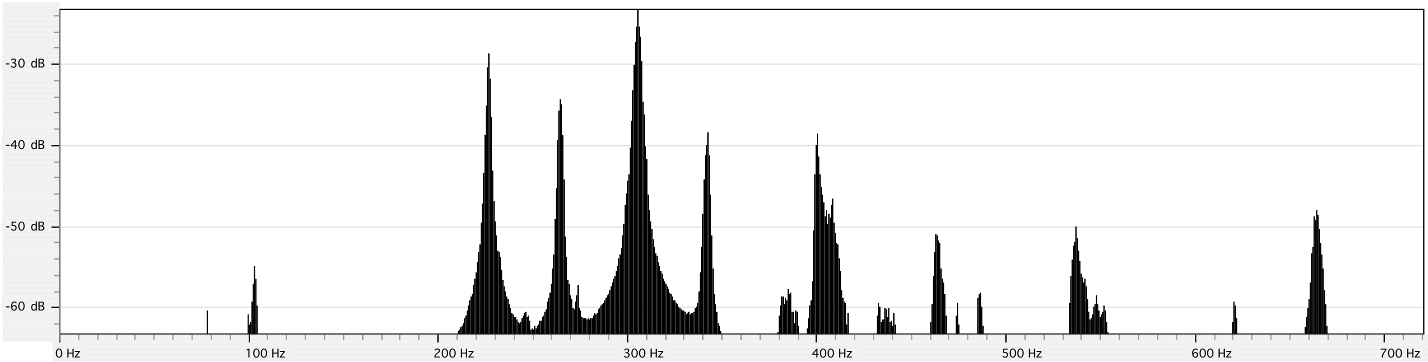

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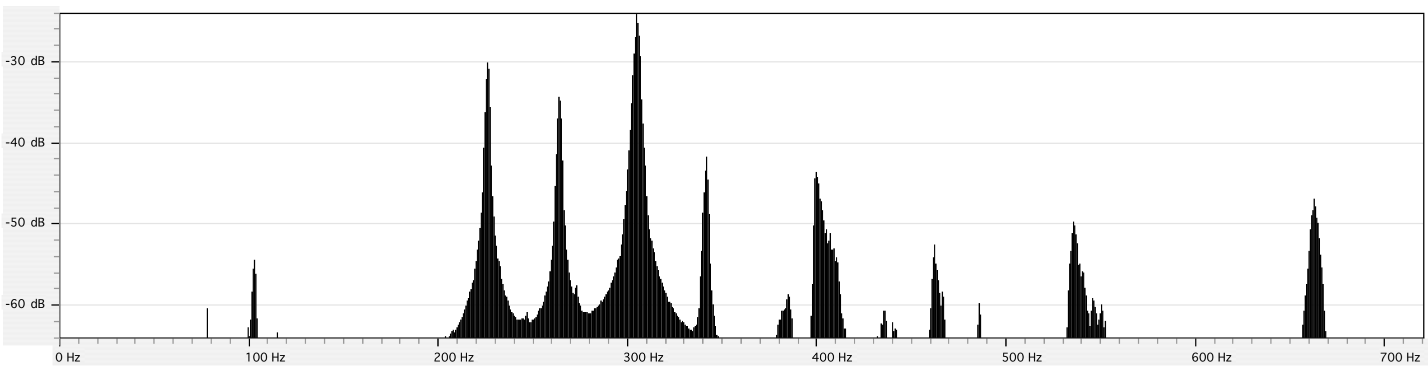

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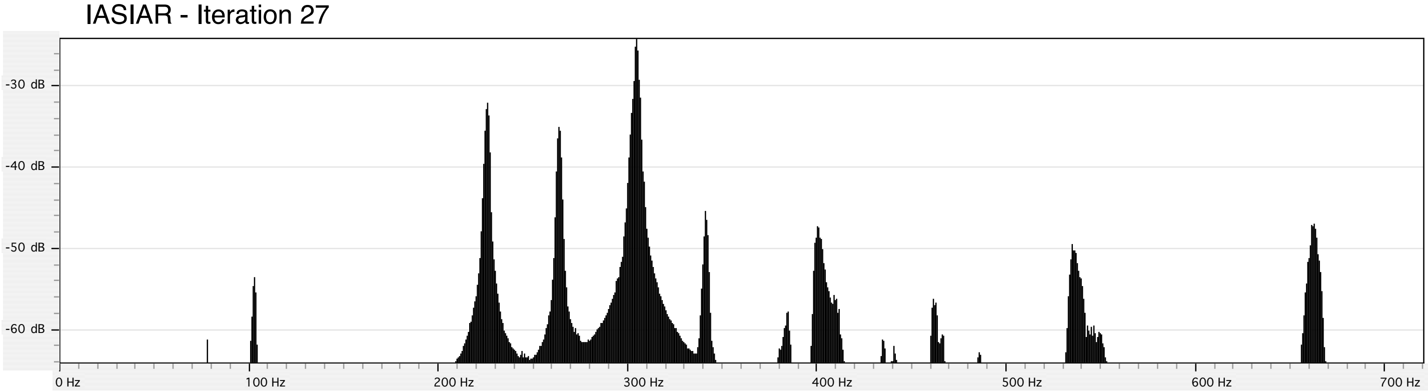

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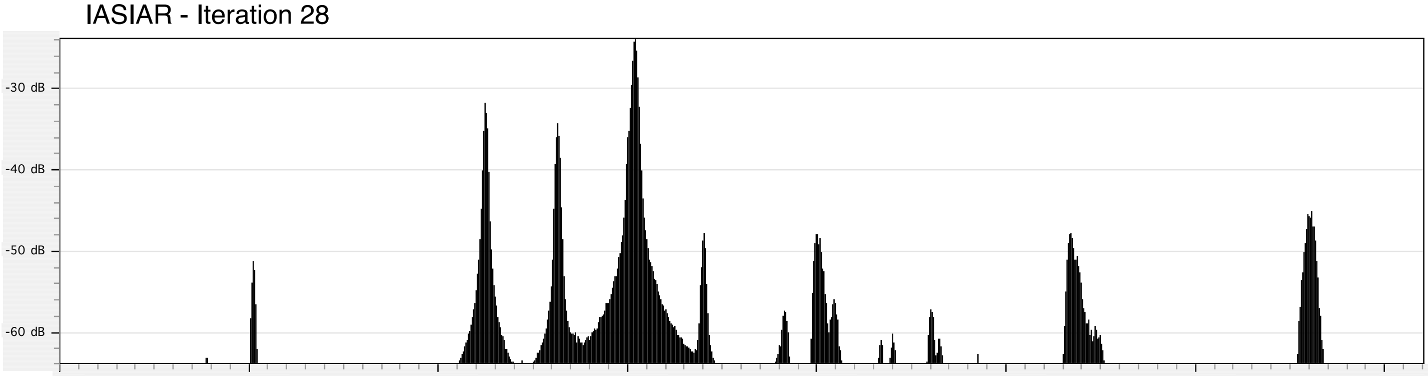

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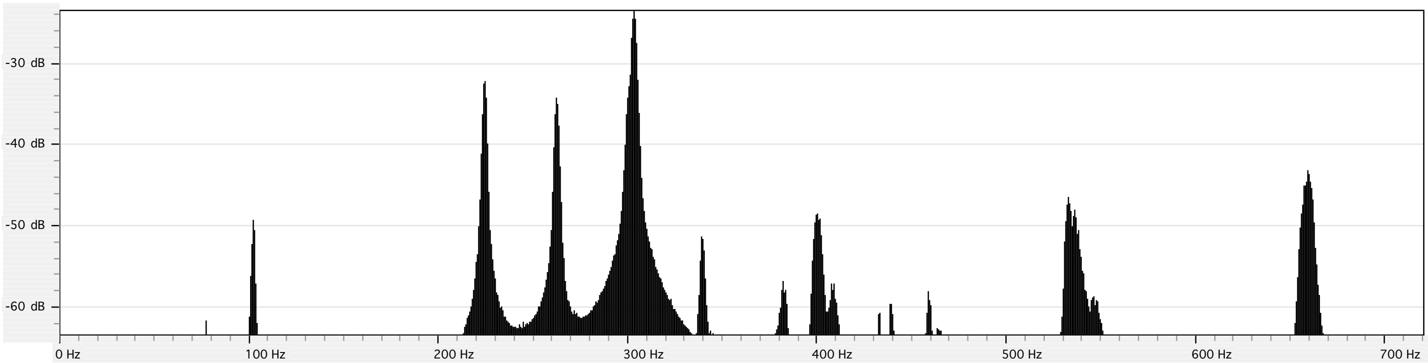

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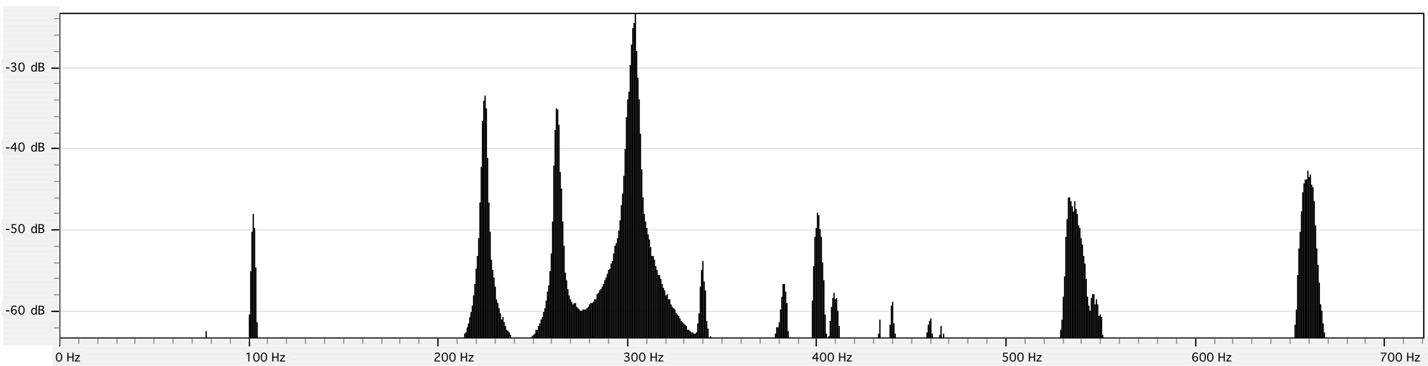

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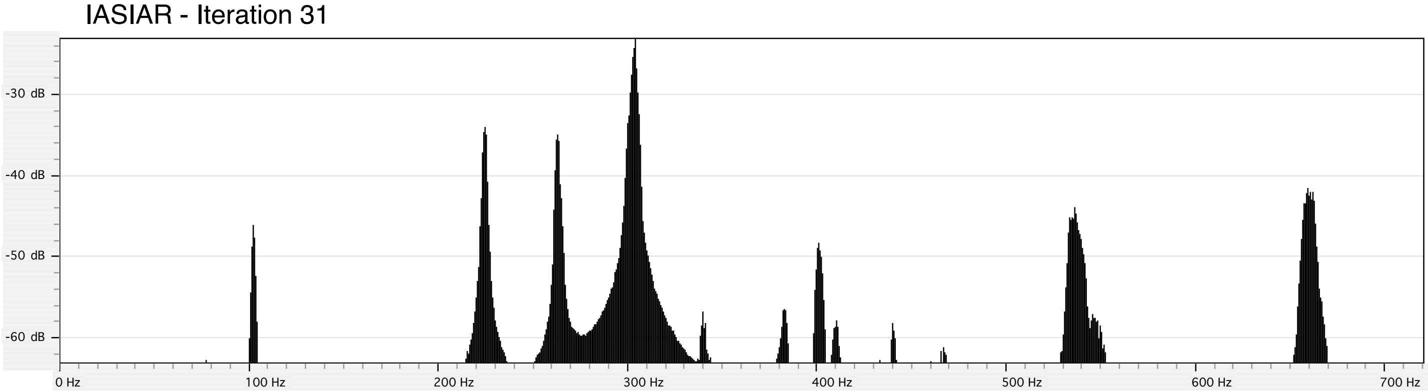

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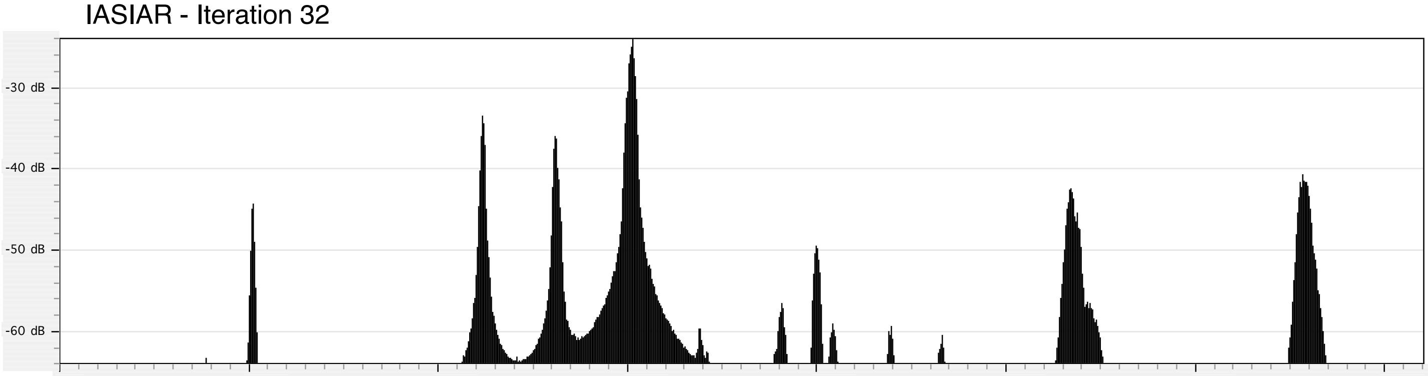
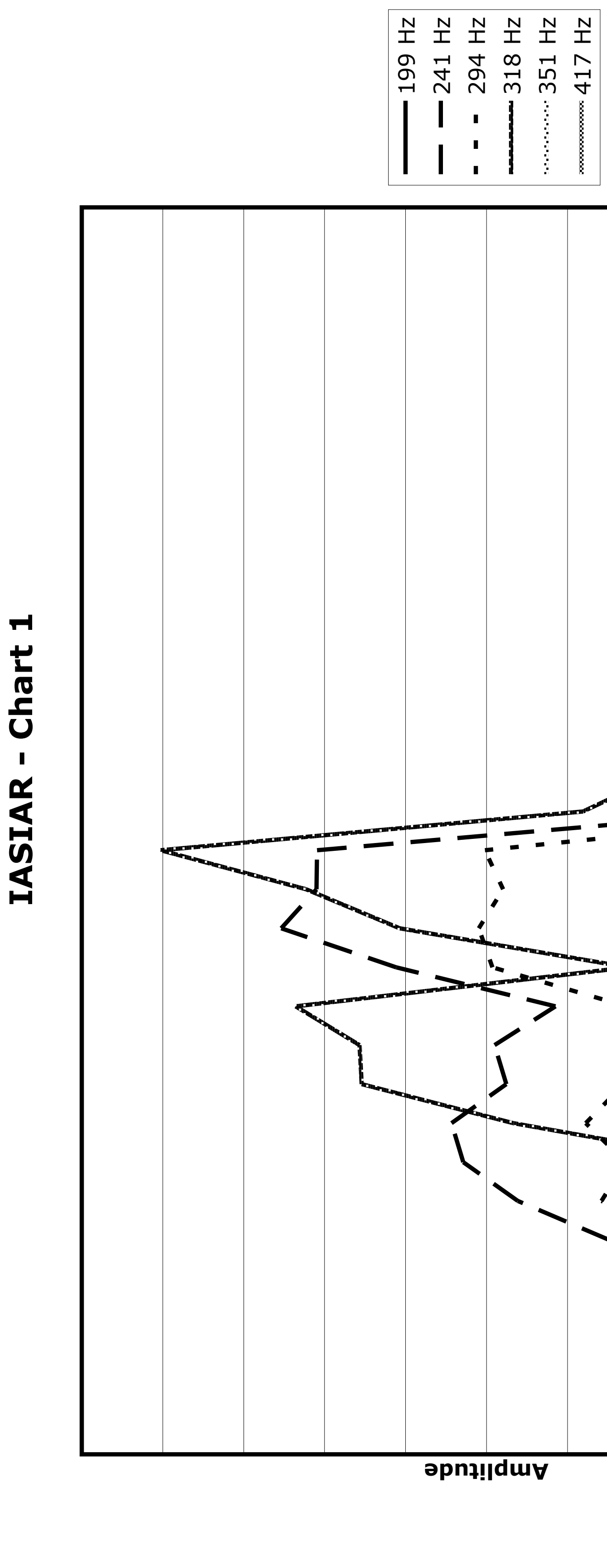
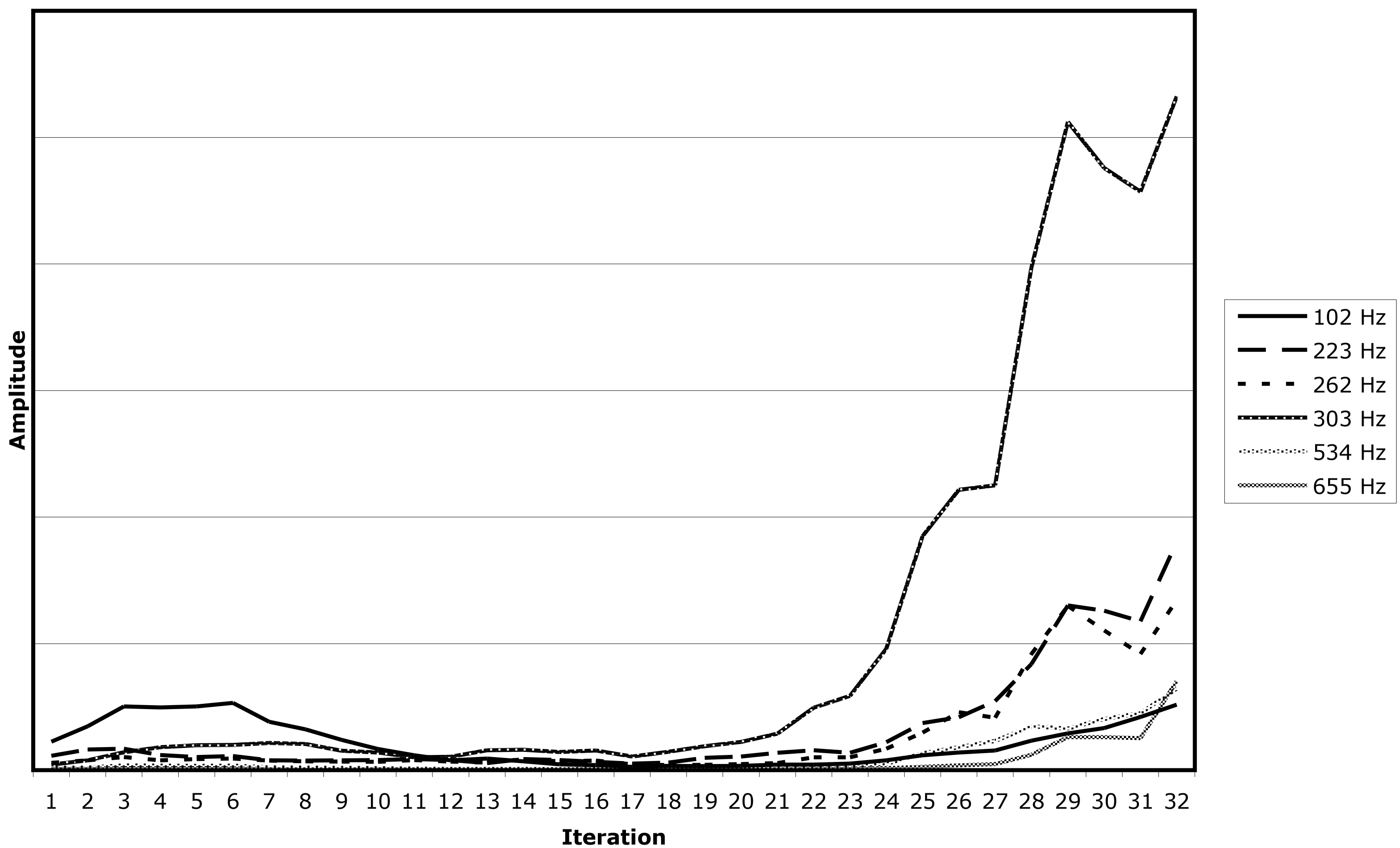
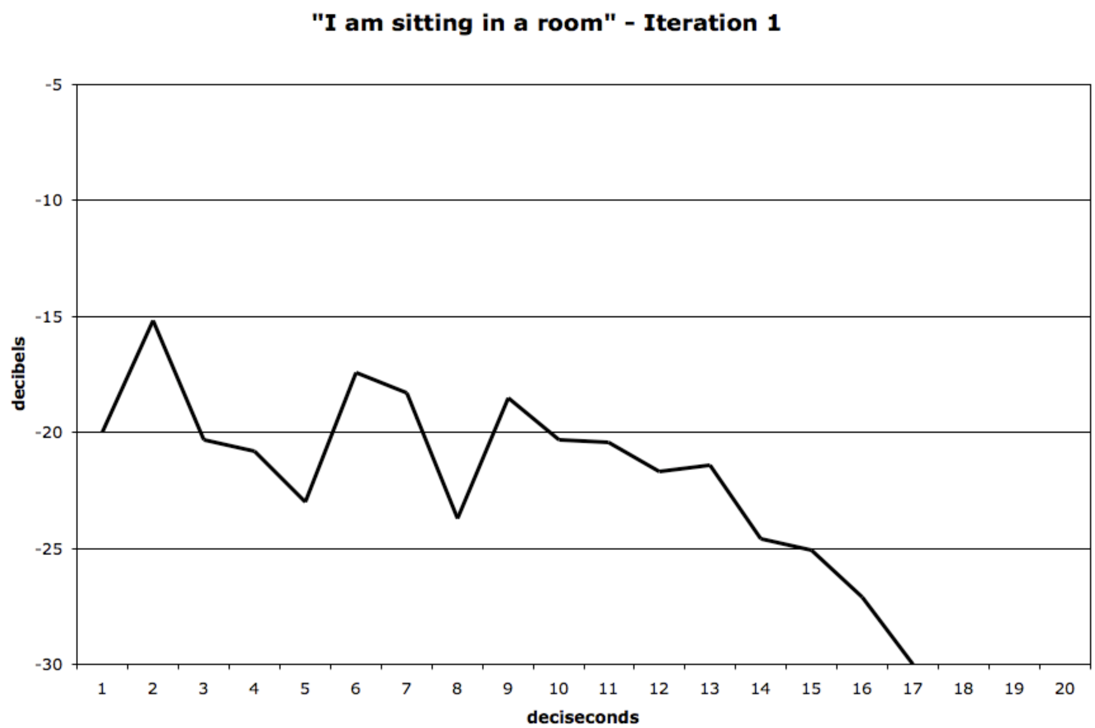
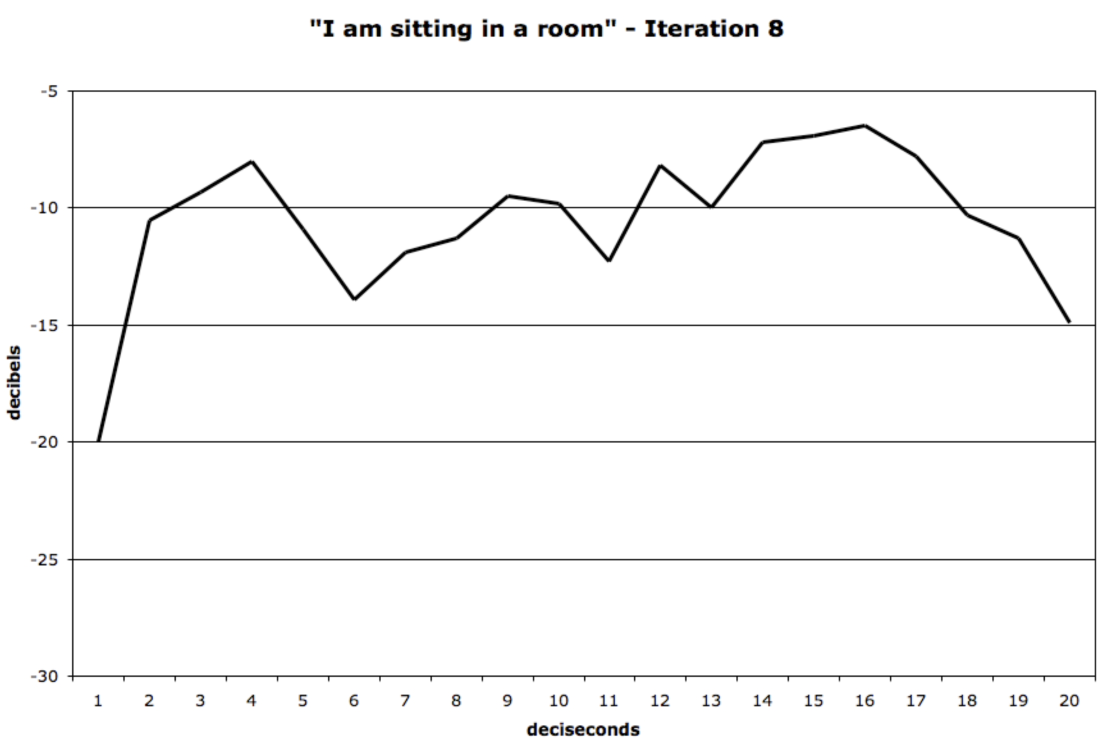



IASIAR - Chart 1
Amplitude
Iteration
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20 21 22 23 24 25 26 27 28 29 30 31 32
199 Hz
241 Hz
294 Hz
318 Hz
351 Hz
417 Hz

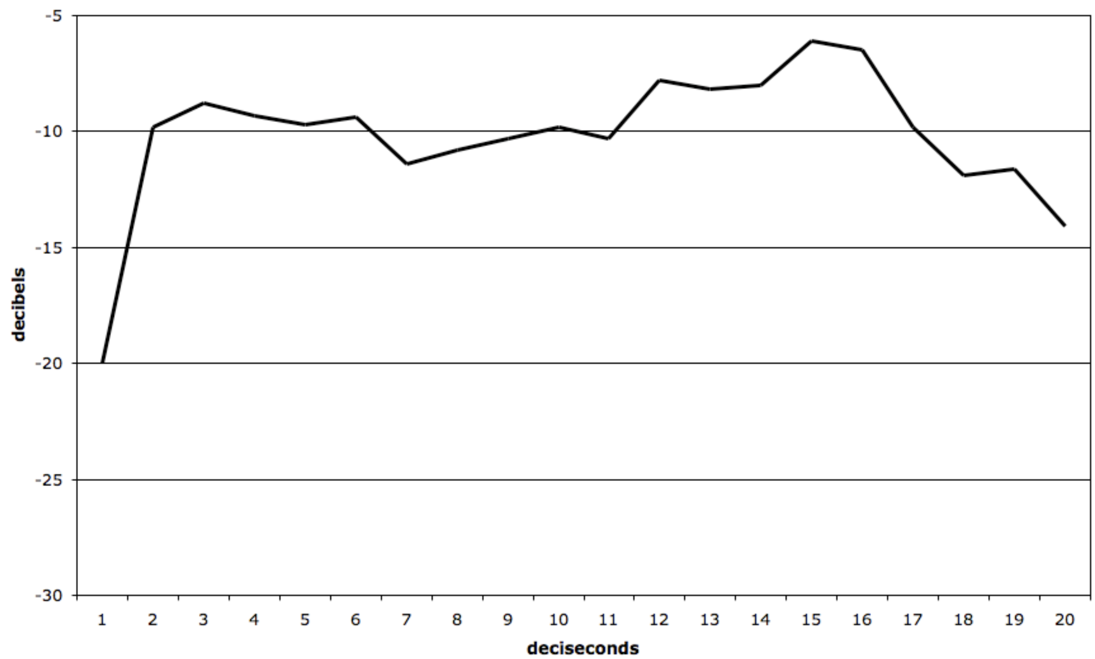
IASIAR - Chart 2



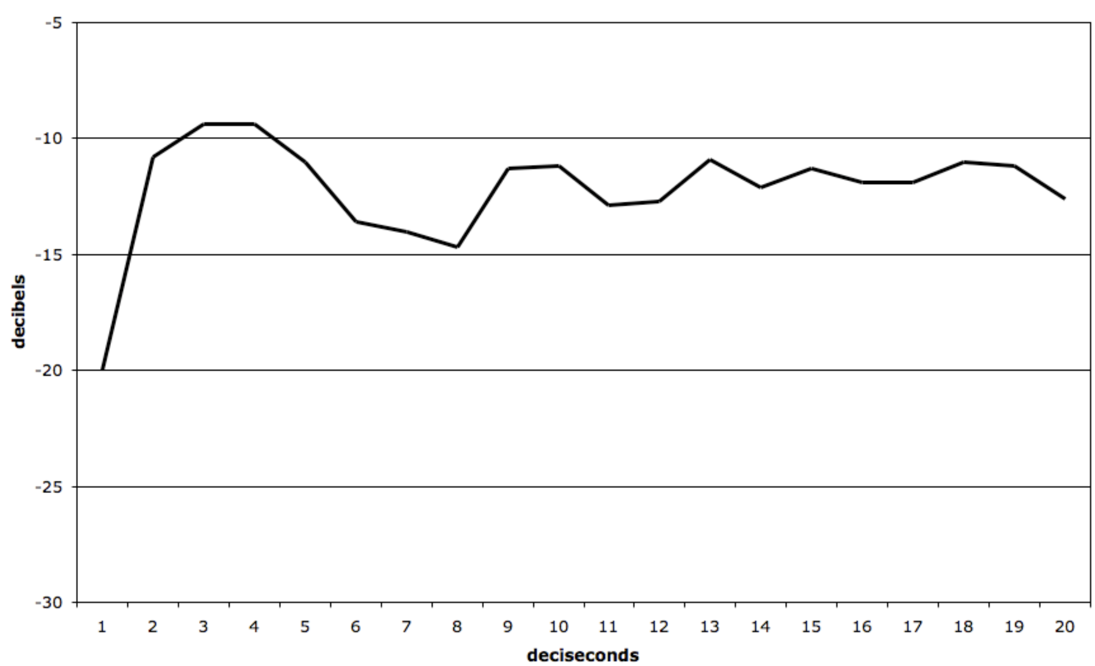

"I am sitting in a room" - Iteration 1
decibels
-5
-10
-15
-20
-25
-30
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20
deciseconds

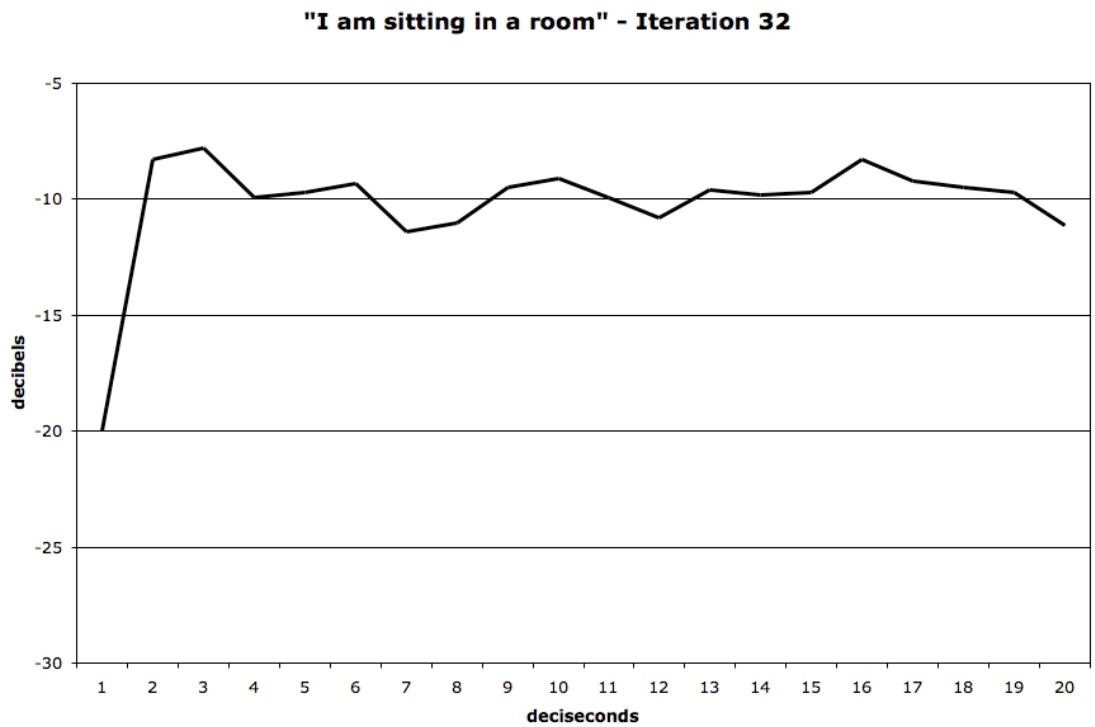

"I am sitting in a room" - Iteration 8
decibels
-5
-10
-15
-20
-25
-30
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20
deciseconds

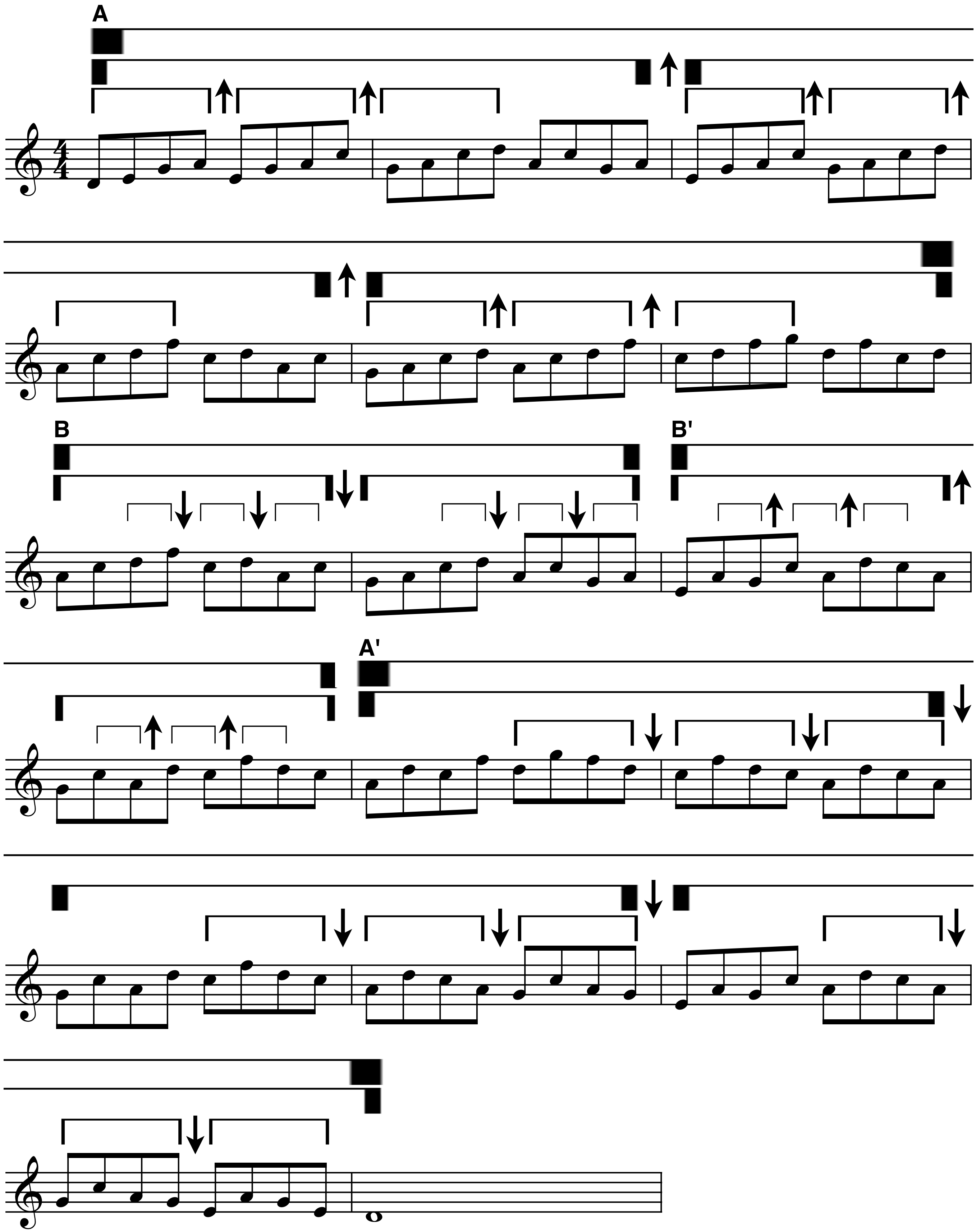
"I am sitting in a room" - Iteration 16



"I am sitting in a room" - Iteration 24




"I am sitting in a room" - Iteration 32
-5
-10
-15
-20
-25
-30
decibels
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15 16 17 18 19 20
deciseconds


A
B
B'
A'

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