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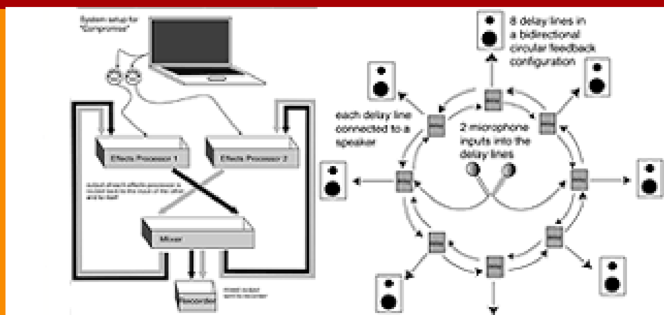

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RECURSIVE AUDIO SYSTEMS: ACOUSTIC FEEDBACK IN COMPOSITION

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ABSTRACT

Compositional and performance experience with a wide variety of audio feedback systems suggests a number of traits common to feedback processes. These systems share not only certain sonic qualities, but also offer highly linked relationships between pitch, timbre, amplitude and time characteristics. These unconventional parameterizations, along with the often unpredictable response of feedback systems to control and input, lead almost necessarily to an improvisational approach in composition and performance. In this article, the authors consider Matthew Burtner's *Study 1.0 (FM)* for radio transceiver and *Delta* for electric saxophone, Christopher Burns' *Letters to André* and *Calyx* for networked effects processors and a realization of John Cage's *Electronic Music for Piano* using a feedback software synthesis instrument.

INTRODUCTION: FEEDBACK AND SYSTEMIC EXPRESSION

Our compositional work with feedback joins the tradition of creatively repurposing artists' tools. Matthew Burtner's * Studies for Radio Transceiver* considers the broadcast and reception of an FM radio system's self-noise, while his *Delta* re-imagines the amplified saxophone as a dynamic network of resonances producing feedback [1]. Christopher Burns' *Letters to André* and *Calyx* exploit commercial multi-effects processors for waveguide synthesis and his realization of John Cage's *Electronic Music for Piano* translates this idea into an unusual form of real-time software synthesis. In each case, acoustic feedback is used to reinvent the capabilities of a given technology.

These reinventions can be thought of as a form of system analysis, where the expressive qualities of the chosen tools (FM radio, the saxophone, effects processors) are revealed. Recursive loops expose the inherent properties of a system, diverting our attention from the content that ordinarily passes through the system to the behavior of the system itself. A central task in composition with feedback is the construction of compelling systems and loops.

These four projects were conceived and realized separately, employ different techniques, and express different musical intentions. However, in discussing them, we noticed that they share a number of common properties: the use of acoustic feedback had substantial ramifications, both for the compositional processes we employed and for the sonic qualities of the resulting music. Feedback seems to have a "nature," aspects of which appear across these divergent musical works. Each shares in the dynamic, articulate, potentially explosive sound of acoustic feedback and in its idiosyncratic response to control.

EFFECTS PROCESSORS AS WAVEGUIDES: *LETTERS TO ANDRÉ* AND *CALYX*

Letters to André and *Calyx* were composed with a hybrid digital/analog feedback system using off-the-shelf electronic music equipment. The feedback system was planned as a low-cost environment for music-making with a unique sonic fingerprint. This system was used actively from 1996 through 1998 to produce fixed-media compositions (recorded first to cassette and later to CD); it was also occasionally pressed into service as an instrument for improvisation.

The system was inspired by André Tavares' experiments with guitar-effects "stomp boxes" connected in feedback loops. An exciting feature of these experiments was the system's ability to generate sound without external input: the self-noise of the analog components of the network could be shaped via feedback into complex sonic textures. The concept of Tavares' guitar-effects network was replicated by recursively patching two digital multi-effects processors through an analog mixer. The new system added the feature of MIDI control over the effects processors, via a computer running sequencing software.

The works composed with this system were essentially all real-time activations of the system, scripted by MIDI control. A single system configuration was used for each piece, without any changes to the audio routing or effects processor patches that would require human intervention in performance or produce audio glitches. The output of the system was recorded without any further editing or manipulation: the feedback loop was treated as the "performer" rather than as a source of material for additional compositional refinement.

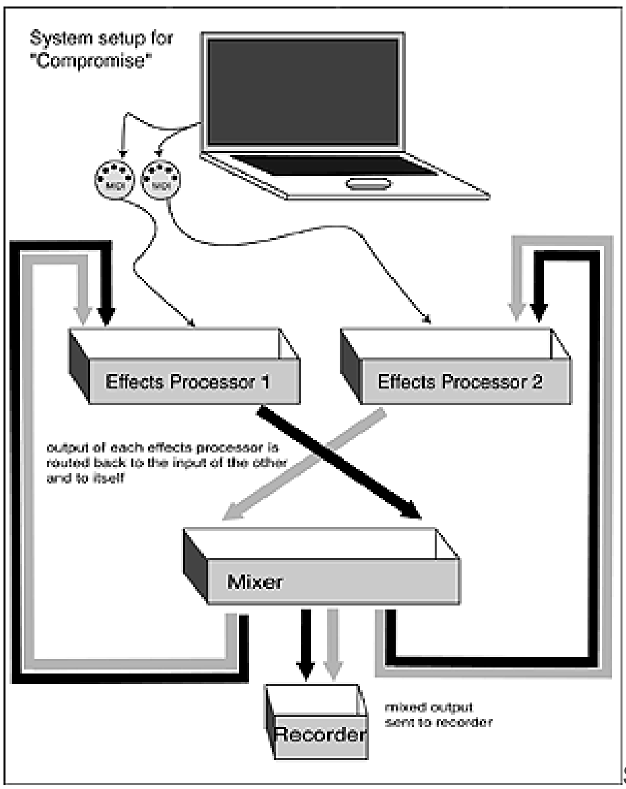
The use of feedback and the philosophy of system "performance" as finished work produced very tight constraints on the compositional process of these pieces. Composition began with configuration of the system hardware, patching together inputs and outputs. Each piece used its own routings between the mixer and the two processors, ranging from a circular stereo path to more complicated parallel configurations.

After connecting the hardware, the next task was programming the effects processors. Standard effects algorithms like reverb, chorus, flanging, pitch shifting, delay and equalization could be selected and combined in parallel or series configurations. The parameters (such as delay time or chorus rate) were then set for each algorithm, with eight parameters designated for real-time MIDI control. Configuration of the system was necessarily done on a speculative and interactive basis; different audio routings and effects settings were tested until a system resulted that produced a promising set of textures for composition.

In use, the behavior of the feedback network was extremely sensitive to its current conditions. The array of sonic possibilities for "the next moment" was totally dependent upon the current state of the system. However, the network was not genuinely chaotic. If musical events were generated from stable rest conditions, they could be reproduced again from those same conditions, not only in broad outlines but also in their precise sonic details. In order to maximize the system's stability and reproducibility, "fussy" mixer settings were generally avoided by setting the faders and sends at unity or maximum. The dynamics of the system (including "start" and "stop") could be controlled using the built-in gain controls of the effects processors (automated via a MIDI sequencer and thus reproduced precisely time after time) – as a result, there was no need to change the mixer settings during the course of a given composition.

Because the sequencer facilitated stable, reproducible output, the system's "performances" could be and were shaped and revised over many months. While the system output was treated as a compositional endpoint, work-in-progress was listened to, critiqued, revised and re-thought as many times as desirable. However, the sensitivity of the system to its current state meant that the flow of composition could only proceed from the beginning of the work towards its end: a change to the parameter data at the beginning of a piece would alter the sonic results throughout. As a result, composition proceeded in chunks. After a short phrase or section was developed and polished, it was fixed, becoming an immutable part of the piece and influencing the development of future materials.

Compromise, the second and shortest of the four *Letters to André,* provides a relatively simple and direct example of the system in use. The piece is an inverted arch: a decrescendo followed by a crescendo, with the loudest moments defined by noisy textures and the quieter segments characterized by echoing, continuously sliding pitches. *Compromise* used a parallel system configuration in which the output of each effects processor was routed to its own input and also the input of the other processor. Both effects processors used pairs of processing algorithms in series: the first box offered a pitch detuner chained to a parametric equalizer; the second used a pitch shifter (with a wider possible range of pitch shifting than the detuner) chained to a delay.



See Figure 1: system diagram for *Compromise* - Ed. note: the figures referenced in this article can be viewed in the online version of LEA at http://lea.mit.edu]

The inverted arch was created by reducing and then increasing the input levels to the detuner, pitch-shifter and delay; additional timbral modifications were produced with simple curves for the parametric equalizer and pitch-shifter settings. The most obvious use of the equalizer comes at the end of the piece, when low cuts and high boosts concentrate the sonic energy into high-frequency noise; the most dramatic change in the pitch-shifting comes at the bottom of the arch, when upward pitch shifts give way to downward transpositions.

The feedback system used for *Compromise* and related works implements what is essentially an idiosyncratic form of waveguide synthesis. Most of the varieties of signal processing available in multi-effects professors, whether pitch-shifting, chorusing or reverberation, can be understood as variations on the basic process of delay. When the feedback routing provided by the audio mixer is also considered, the system is essentially an implementation of the recursive delay structures which are the building block of waveguides. The analogy has more to do with principle than practice - one would be hard pressed to implement waveguide models of acoustic instruments using this equipment, and there are no real-world acoustic interpretations of the processor networks. However, the system shares an articulate and continuously varying sonic character with more conventional forms of waveguide synthesis.

The recursive nature of the audio path makes the system dependent upon its analog components for tolerance of overload. Both the mixer and the inputs to the effects processors occasionally overload or clip; with careful gain settings, the overloads can be concentrated in the analog sections of the network and digital clipping minimized. However, the system is not sonically pristine: audible grit and clicking are a necessary part of the music.

FEEDBACK IN THE DIGITAL DOMAIN: *ELECTRONIC MUSIC FOR PIANO*

Inspired by the waveguide analogy, more recent projects have involved fully digital implementations and variations of the hybrid feedback system described above, using software synthesis platforms like Pd and Common Lisp Music. One important difference between the hybrid analog/digital model and the software versions is that all-digital systems require external excitation. Software models have no self-noise and will not sound without some kind of input stimulus. The software networks must be excited by injection of an impulse, a noise burst, an arbitrary sound recording or a live microphone input.

A larger challenge for software implementations is gain control; digital feedback structures have an extremely small threshold between silence and explosive clipping (The problem can be avoided by using damped feedback – that is, feedback scaled by a coefficient less than unity – and continuous excitation, as in traditional waveguide applications for physical modeling. However, the models for these projects are self-generating and essentially undamped). Complex network topologies only become possible when automatic gain control techniques like peak-limiting compression or waveshaping are applied [2].

One software feedback system was implemented for a realization of John Cage's *Electronic Music for Piano*, first performed by Christopher Burns and pianist Christopher Jones in May 2002. *Electronic Music for Piano* is perhaps one of Cage's most permissive scores. While the range of possibilities - electronics and piano or pianos - is more circumscribed than in works for indeterminate groups of performers like the Variations series, *Electronic Music for Piano* lacks the systems of discipline associated with that series. The handwritten prose score (complete with Cage's strikeouts and emendations) consists only of lists of potential technical means – "feedback, and changing sounds (microphones, amplifiers, loudspeakers – separate system for each piano)," and suggestive metaphors to guide action ("observation of imperfections in the silence in which the music is played" [3].)

Electronic Music for Piano is dedicated to David Tudor; presumably the "permissive" characteristics described above have much to do with Cage's trust in his friend and colleague Tudor, as well as the shared culture they developed through extensive collaboration. The dedication can also be viewed as another kind of suggestion for performance. Our realization of *Electronic Music for Piano* is not only a digital translation of the work with hybrid feedback systems, but also an homage to David Tudor's homebrew analog feedback systems [4], now reinvented with digital components and deterministic controls.

The feedback network is implemented in Pd, with a circular array of delay lines feeding each other and eight loudspeakers. Audio signals are passed around the circle in both clockwise and counterclockwise directions, with waveshaping functions to prevent clipping at every stage where signals are combined. Each delay time is continuously varying, with linear interpolations between randomly generated values over randomly selected lengths of time. This process was developed in response to another of Cage's suggestions:

as though there were

take a drawing of the controls

(volume, tone) available and –

on a transparency – transcription

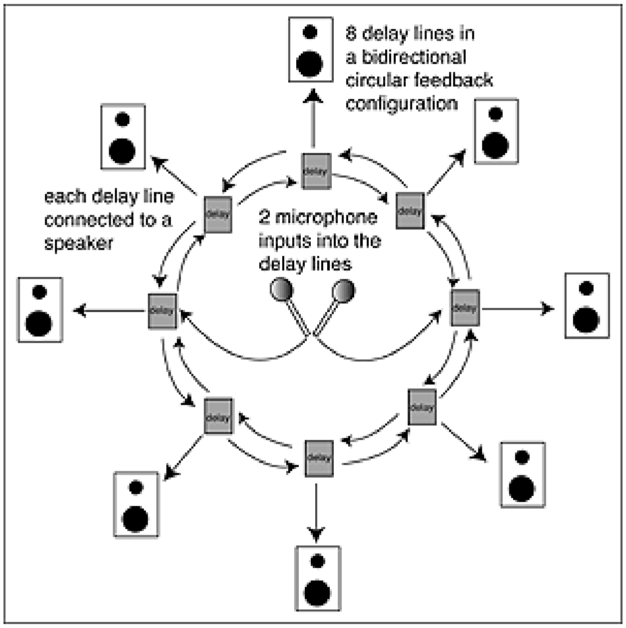
for astronomical atlas suggesting

were it would

which (^ superimposed) ^ gives

suggestions for use of controls (not explore)[5]

The electronics operator - through a series of control parameters - and the pianist, via the microphone inputs, have influence over the feedback network. However, they do not have command of the process; the randomly generated parameters and the generally idiosyncratic behavior of feedback make the output of the system unpredictable. Sometimes the feedback imitates events played at the piano very precisely, sometimes it remains quiet during busy passages and sometimes it bursts into noise in the middle of a long silence.



[Figure 2: system diagram for *Electronic Music for Piano*]

This is the unusual aspect of this realization and instrument; the electronics are designed to guide the operator's musical choices, just as the operator guides the electronics. There is a symbiosis of piano, pianist, electronics and operator; in performance the situation is one of improvising with the electronics, rather than using the electronics to improvise. David Tudor said, "I want to find ways of discovering something you don't know at the time that you improvise.... The first way is to play an instrument over which you have no control, or less control than usual" [6]. In this realization, the instability of the feedback system makes it an equal partner in the improvisational process.

As with its analog/digital model, the software feedback system produces complex sonic textures, articulate melodic gestures and other interesting emergent behaviors. It creates a rich palette of unusual and continuously evolving sounds; the unpredictability of the feedback provides both a compelling musical element and an interesting challenge to the performers in the semi-improvisatory environment of *Electronic Music for Piano*.

THE ELECTRIC SAXOPHONE AS A FEEDBACK CONTROLLER: *DELTA*

The musical use of acoustic feedback is closely tied to the development of amplification. In musical instrument design, feedback is especially important for the development of the electric guitar. Perhaps most famously, Jimi Hendrix redefined guitar performance with his groundbreaking performance of "The Star Spangled Banner" at Woodstock in 1969. Hendrix abandoned traditional notions of guitar performance, using the instrument as a feedback controller. Hendrix's performance practice, and especially the Woodstock "Star Spangled Banner," inspired the composition of *Delta* (2001), a work for solo saxophone. The electric guitar, as played by Hendrix, provides a model for the reimagination of the saxophone as an electric feedback instrument.

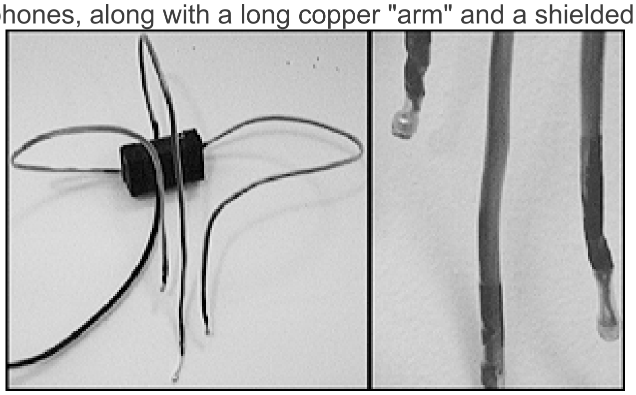
In *Delta*, small microphones embedded inside the saxophone are used to capture resonances within the air column. Feedback between the internal microphones and external loudspeakers is generated and then controlled by opening and closing keys and by changing the air pressure in the column. The saxophone body becomes a filter, dynamically modifying the feedback signal via changing instrumental resonances.

The electric saxophone grew out of the Metasaxophone Project [7], an ongoing effort since 1997 to extend the properties of the saxophone through new performance techniques and technologies. The saxophone is enhanced as both a computer controller and as an acoustic signal generator. The idea to explore the saxophone as an electric feedback instrument arose from a desire to carefully capture the audio signal as a control signal for use in interactive electroacoustic music.

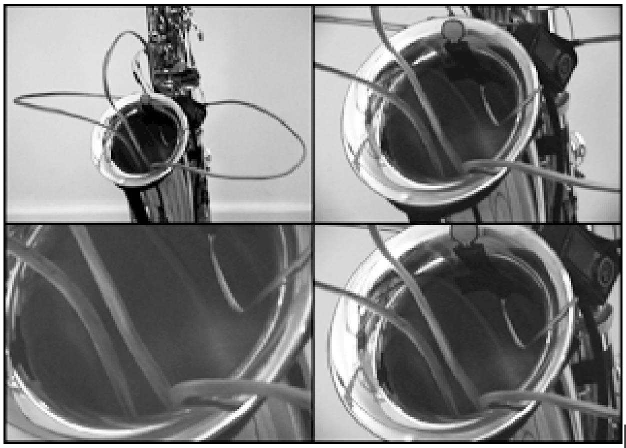
Using sensor technology and a microcontroller on the bell of the instrument, the Metasaxophone captures constantly changing performance data and converts it to continuous MIDI control change messages. This data is used to extend the gestural interface of the acoustic saxophone; the player can generate control data with techniques such as finger pressure and saxophone position, which do not affect any simultaneous acoustic activity with the instrument. The Metasaxophone as a MIDI controller debuted in 1999, in performances of *Noisegate 67*. This new controller continues to be used in a number of ways to extend the instrument [8].

Because the sensor-based modifications to the Metasaxophone do not alter the acoustic sound of the instrument, the native sound of the saxophone can be used in performance or interpreted as another type of control parameter. The continuing acoustic viability of the instrument makes amplification and acoustic feedback possible; hence the "electric saxophone," or Metasaxophone Audio System. The electric saxophone is based on a set of small electret condenser microphones inserted inside the instrument. The electret capsules used are Panasonic WM60-ATs, chosen because they feature good frequency response (20 to 20,000Hz), less than 2.2kOhm impedance and resilience under difficult environmental conditions, vibration and shock. Additionally, the omnidirectional polar pattern of the microphones aids the propagation of feedback in the air column.

The microphones, along with a long copper "arm" and a shielded cable, were threaded through heat-shrink tubing

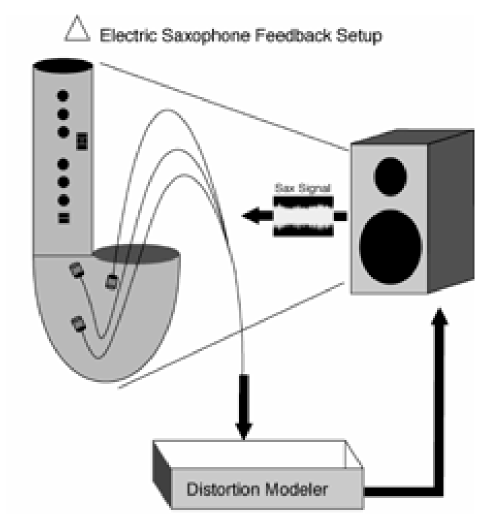
[Figure 3] . 

The resulting bendable arms are then rearranged to suit the specific miking situation desired. The three arms attach at the top of the bell of the saxophone


[Figure 4] ; from there, the three shielded audio cables are combined into a snake that runs to the audio equipment. The microphones each have a different audio output, so that their signals can be routed independently.

Once the microphones were operational, experimentation helped define the saxophone performance techniques that would enable the instrumentalist to control acoustic feedback. With the microphones in place, a series of acoustic measurements were taken of the interior of the saxophone. These tests suggested the range of filter responses the saxophone will exhibit when placed in an audio feedback loop, and demonstrate the relative efficacy of various techniques applied in performance.

In *Delta* (2001), the Metasaxophone audio system becomes the basis for an electric feedback instrument. The continuous control properties exhibited in the acoustic tests became meaningful musical controls, extending the capabilities of the saxophone.



[Figure 5 shows the technical setup for *Delta*.]

The saxophone sound is picked up by the microphones in the bell and output through the loudspeaker, where it is again picked up by the microphones inside the bell, now filtered through the body of the saxophone. The instrument feeds back and the performer can control the resonant frequency by changing the properties of the tube with fingerings. In keeping with Hendrix's inspiration, the microphone outputs are sent through a distortion box that emulates the type of overdrive distortion characteristic of electric guitars and tube amplifiers.

Because the saxophone body is not solid, the instrument cannot be overdriven, and attempts to create true overdrive distortion only overdrive the microphones. The distortion box creates the sound of distortion without the need to increase the gain of the audio system to unmanageable levels. In addition, the use of distortion introduces a wider frequency range that approaches the noise signals used in the acoustic tests. The broad spectrum allows for the activation of a variety of resonant frequencies in the air column.

The performer controls the feedback loop by forming an embouchure and applying different air pressures through the mouthpiece, and by changing keys on the instrument, either rapidly or in a slow, deliberate fashion: as with the Metasaxophone's pressure-sensitive sensors, the intention is to transform the discrete switches of the saxophone keys into continuously variable controls. Performance confirms that the frequency response of the instrument changes slightly as keys are slowly depressed or released. The changing internal state of the saxophone alters the air column, creating different, and often multiple, resonant frequencies.

The feedback loop has a pronounced effect on instrumental performance practice. In an ideal performance, no audible sound emits from the saxophone, and the audience hears simply the changing distortion and feedback as it is shaped by the saxophone body and activated by key clicks. In reality, however, the rapid changes in air pressure in the instrument inevitably cause acoustic byproducts - high squeaks, air hisses and honks - that are then amplified, distorted and fed back into the system.

Delta is highly unstable, and as such is permitted to be different for each performance. A score prepared for use in concerts in 2001 outlines in a tablature notation the fingering combinations to be used, embouchure pressure changes over time, and the formal conditions of the performance in the form of time-line energy changes. From the score, it appears that the performer has great freedom to shape the dramatic flow of the piece, but in actuality the freedom of the performer is closely curtailed by the instability of the system. Much like surfing on a breaking wave, the performer of *Delta* makes decisions about movement "on-the-fly," responding immediately to the system in order to keep the piece alive. The score outlines ideas that are always modified in performance due to the unpredictability of the system. [Figure 6 shows the score of Delta prepared for a performance at Stanford's CCRMA in 2001.]

The score contains up to five staves for the saxophone part. The "Sound" staff gives a graphic overview of the time/energy development of the piece and includes indications such as "cause/allow beatings," "very light tonguing to bring out squeaks," "changing key clicks" and "teeth on reed." The "Fingering" staff provides suggested key fingerings and gives descriptive "microkeying" indications such as "Ad lib low Bb attack to G#, insert periodically," "very slow changes of key - slight closing/opening," and "lift Bb key 1/4." In the beginning of the score, a "Sounding Pitch" staff appears at the top of the page, revealing the tritone structure that acts as the opening of the piece. This staff disappears on subsequent systems as pitch becomes something difficult or irrelevant to control. The "Air Pressure" staff uses a notation for pressure and gives indications such as "talk into horn while playing." The "Electronics" staff was used to give indications of changes in the distortion boxes or any other electronics.

In the performance this score was prepared for, a computer drum machine (the polyrhythmicon) was used to create frenzied accelerating beats behind the electric sax. A dense polyrhythm with a tempo relationship of 90 BPM (beats-per-minute): 60BPM: 120BPM gradually accelerates to 120BPM:180BPM:250BPM. This electronic part is not necessarily a permanent feature of the piece, and like all other aspects of the piece it can be changed or ignored. It was added to augment the tension of a hyper-frenetic performance system.

Despite the existence of a score, the composition of the piece was worked out in rehearsal and it is always recomposed in performance. The score is simply a guide for the performer, a repertoire of ideas and a memory aid for an instrument that can be quite disconcerting to play. Although the piece is different every time, it does have a clear identity and the score helps capture that, even as the system simultaneously subverts repetition.

The Greek letter ? (Delta), originally meaning "door," is a threshold or barrier at an opening, such as a sandbar at the mouth of a river. It is also the mathematical symbol for change. The saxophone body is viewed as a type of threshold or doorway into a world of rich change and dynamic transformation. Subsequent performances of the piece will use the same title, possibly with version numbers for significant changes.

CONCLUSIONS: SYSTEM DESIGN AND COMPOSITIONAL PROCESS

Although the works described here display different approaches to performance and aesthetic intentions, the common use of acoustic feedback leads to a number of other similarities between pieces. Most obviously, the sonic fingerprints of feedback are present in each. Whatever other sounds may be present, each composition trades in some way on the whistling, melodically articulate resonances characteristic of feedback. Grit, distortion, and other "lo-fi" artifacts are also common, even in the software implementation of *Electronic Music for Piano*.

In each case, system design was a major component of the compositional process. As with much electroacoustic music, the arrangement and configuration of the electronics determined the range of sonic and compositional options for each piece. The most extreme example presented here is *Study 1.0 (FM)*, where the compositional work was, in essence, the conception and design of the electronic system.

The configurations of our feedback loops rarely allow for the direct and independent control of important musical parameters like pitch, rhythm and timbre. The performer of *Delta* fingers an E on the saxophone; at least some sonic change will be initiated and, at best, the system will resonate at some frequency in the harmonic series above the fingered E. Similarly, the composer working with a network of effects processors might change the length of a delay line in the hopes of creating a glissando or other variation in pitch. The composer and performer have the feeling of influencing the system, rather than controlling it.

This sense of engaging with a system, rather than commanding it, is strengthened by the dependence of feedback systems upon their current state. In each of the systems described here, the range of available sounds is highly dependent upon the current contents and conditions of the system. Typically, composers and performers have nearly their entire chosen sonic palette available at any moment. With feedback systems, this is not the case; future activity is limited and channeled not only by the composer's decisions, but also by the history of the audio system itself. A texture or sound, achieved with a certain system configuration or parameter setting at one point in a piece, may not be repeatable at another moment.

As a result, much of our compositional work with feedback systems is improvisational, even when the completed work is relatively fixed, as with *Study 1.0 (FM)* and *Compromise*. The potentials of the system at any moment and the range of influence of the controls can only be explored through improvisation. The complex, "messy" responses of feedback systems necessitate an intuitive approach in composition and performance; formal and sonic complexities result from the emergent properties of the system, interacting in the moment with the composer and performer. Feedback systems will speak for themselves.

REFERENCES AND NOTES

1. A detailed discussion by Burtner of this work is available in the current issue of *Leonardo Music Journal* (LMJ 13, "Regenerative Feedback in the Medium of Radio: Study 1.0 (FM) for Radio Transceiver," by Matthew Burtner). For a brief description of the article, see http://mitpress2.mit.edu/e-journals/Leonardo/isast/journal/toclmj13.html .

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ABOUT THE AUTHORS

Christopher Burns

Christopher Burns' recent compositional activity focuses on chamber music. His experience as a computer music researcher is a major influence on his acoustic composition; his newest works are written with pitch and rhythmic structures that are created and transformed using custom software. One of these pieces, a sextet entitled * The Location of Six Geometric Figures* , was recently awarded first prize by the Hitzacker Summer Music Festival. This work has been performed by ensemble recherche in Germany, ensemble Gageego! in Sweden and the San Francisco Contemporary Music Players in California.

Burns is the Technical Director of the Center for Computer Research in Music and Acoustics (CCRMA) at Stanford University, where he has completed a doctorate in composition, and is pursuing a second in computer music research. He has studied composition with Brian Ferneyhough, Jonathan Harvey, Jonathan Berger, Michael Tenzer and Jan Radzynski. His research interests include algorithmic composition techniques, the application and control of feedback in sound synthesis, and the study and preservation of sketch materials produced by electroacoustic composers.

Burns co-curates the * sfSoundSeries* concerts in San Francisco and the * Strictly Ballroom* concert series at Stanford; both venues feature contemporary music performed by local and international guest artists. These concert projects are also an outlet for his interest in the realization of classic electroacoustic music; recent projects include the creation and performance of new versions of works by Cage, Ligeti, Lucier, Nancarrow and Stockhausen.

Matthew Burtner

Matthew Burtner's music has been described by *The Wire* as "some of the most eerily effective electroacoustic music I've heard," and *21st Century Music* writes "There is a horror and beauty in this music that is most impressive." His work regularly combines instrumental ensembles, computer technology, interactive acoustics and multimedia.

Burtner is currently Assistant Professor of composition and computer music at the University of Virginia, where he is associate director of the VCCM Computer Music Center. A native of Alaska, he studied philosophy, composition, saxophone and computer music at St. Johns College, Tulane University (BFA, 1993), Iannis Xenakis' UPIC Studios (1993-94), the Peabody Institute of the Johns Hopkins University (MM 1997) and Stanford University's CCRMA (DMA, 2002). He has been composer-in-residence at the Banff Centre for the Arts, Simon Fraser University in Vancouver and the IUA/Phonos Institute in Barcelona. His original computer music research is presented regularly at international conferences and it has been published by journals such as *Organized Sound*, *The Journal of New Music Research* and the *Leonardo Music Journal*. His music has been recorded for Innova (USA), DACO Records (Germany), *Computer Music Journal* (MIT Press) and Norway's Eurydice label.

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