IEEE pervasive COMPUTING
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Vol. 7, No. 3
July–September 2008

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A composer's view of the history of hardware hacking, contrasting the aesthetic implications of circuitry and software.

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Once upon a time, computers were not pervasive. Lead users used lead solder instead. Or at least they did in my field: experimental and electronic music. Mainframe computers didn't fit into instrument cases; homemade circuits did.

With the emergence of microcomputers in the late 1970s, the action began to shift from hardware to software. But today, after three decades of increasingly digital musical culture, analog circuitry has experienced something of a comeback. Circuit bending, hardware hacking, and visual artists' enthusiasm for things physical have fostered a revival of interest in tactile alternatives to software.

This article traces the history of my engagement post-Cagean music, with an eye toward technological innovation and its aesthetic implications.

When circuits ruled

It's a familiar enough story: as a teenage musician, I was undistinguished at best, but the pop music of the late 1960s drew me to electronic sound. In 1971, having reached the limits of what I could accomplish with a guitar, flute, and fuzzbox, I bought a used Tandberg reel-to-reel tape recorder. It contained a hidden, undocumented switch that, when thrown, induced delicious, semicontrollable swoops of feedback. (What strikes me as significant in retrospect is that this switch transformed a recording device into a performance instrument. The buttons and knobs that would normally initiate and adjust the direct transfer of acoustic sound to tape became the interface for manipulating electronic sounds.) I was smitten by the siren call of electronic music but unable to afford any of the instruments available at the time: Moogs, Arps, and Buchlas synthesizers were still the playthings of pop stars and universities.

Integrated circuits, on the other hand—the guts of those costly machines—were getting cheaper in inverse proportion to their sophistication. These chips contained 90 percent of a functional circuit designed by someone who really knew what he (almost all of the engineers at the time were male) was doing; the remaining 10 percent could be filled in by someone clueless, like myself. The trick was finding the right chips and application notes. In the days before the World Wide Web, information was much more compartmentalized, with precious few leaks. When data did trickle down from the engineers to amateurs through hobbyist magazines, it was passed from hand to hand like samizdat literature.

My first chip was a Signetics SE/NE 566 Phase Locked Loop (www.datasheetarchive.com/NE566-datasheet.html). Intended as the bleating heart of the (then novel) Touch-Tone telephone, this was an "oscillator on a chip." Although not quite so versatile as one from Robert Moog's hand, at US$5, it was considerably

Published by the IEEE CS ■ 1536-1268/08/$25.00 © 2008 IEEE

cheaper. (Years later, I discovered that this same IC was the heart of the electronic *sruti* box, Paul DeMarinis' first circuit, and David Behrman's extraordinary homemade synthesizer. This one chip might have been to the development of American electronic music what the Stratocaster was to the rise of rock and roll.)

My chip sat regally in the center of an oversized prototyping circuit board, encased in a phenomenally ugly (yet to me very professional looking) metal box with a crinkly matte-black finish, festooned with orange Dymo labels that officiously designated the mismatched knobs, switches, and jacks as "pitch," "on," "output," and so forth. Ugly or not, this box not only made electronic music the moment I turned it on, it also twisted truisms that might otherwise scare off a young experimentalist: anything worth doing is worth doing wrong, and two wrongs can make a right—these became my house rules for hardware hacking.

The last few months of high school were spent in my bedroom—with a microphone, the warped Tandberg recorder, and this oscillator—making electronic music. My instruments were crude but eminently playable. Yet I played for an audience of none in my parent's apartment, while the pop music I knew and loved was filling concert halls and clubs. I wanted to take electronic music out of the bedroom, but I didn't know where to start.

Interaction and improvisation

In the fall, I started college at Wesleyan University and met Alvin Lucier, a composer who didn't own a piano, didn't write for conventional instruments (much less play one), and yet had an active career as a "composer/performer." His 1969 work, *Vespers*, in which blindfolded players use hand-held, click-emitting sonar devices to navigate through the performance space,[1] bore no obvious resemblance to any existing form of music. Yet somehow it embodied the essential characteristics of live performance, such as ensemble interaction and acoustical sensitivity.[2] It reconceived the musical score as a task to be solved and, despite Lucier's aversion to the term, depended heavily on what could only be termed "improvisation."

For me, this latter trait was the final piece of the puzzle: the link between the "high art" of the European classical tradition (in which even a maverick like Lucier was deeply rooted) and all those other musical genres in which I felt more comfortable, such as pop, blues, and jazz. I posited that the breakthrough character of a piece like *Vespers* was inextricably bound to the abandonment of traditional instruments, with all their "cultural baggage" (to disinter a cliché of the time) and the embrace of new electronic resources.

Inspired by Lucier's example, I discarded all the instruments and many of the musical preconceptions I had brought with me to college and began developing new electronic tools of my own, suitable for live performance. Some were simply adaptations or reconfigurations of familiar devices, such as a speaker and microphone set up to feed back. In my composition *Pea Soup (1974–76)*, for example, a self-stabilizing network of phase shifters nudges the pitch of audio feedback to a different resonant frequency every time feedback starts to build, replacing the familiar shriek with unstable patterns of hollow tones.[3] It's a site-specific raga reflecting the room's acoustical personality. These architectural melodies can be influenced by moving in the space, making other sounds, or even letting in a draft of cold air. In *Pea Soup*, I combined the affordable electronics with which I was familiar, the architectural acoustics that Lucier brought to my attention, and a classic minimalist, task-oriented score. Through this work and other feedback pieces, I learned that new instruments and sound materials often suggest new musical forms—the architecture determines the tuning and scale, for example—at the same time that they rule out conventional ones.[4]

My approach to design lay somewhere between a Jasper Johns-ian version of "reverse engineering" and a simian typing pool's attempt at Shakespeare.

I continued to build my own circuits. Possessing neither the instinct nor the intellectual tools for a proper study of electrical engineering, I picked up knowledge piecemeal: I scrutinized designs in engineering journals; I stole bench space in a physics lab; I sat at Behrman's feet during his artist's residency; and eventually I joined David Tudor's "Composers Inside Electronics" group.[5]

My approach to design lay somewhere between a Jasper Johns-ian version of "reverse engineering" (take something apart, copy it, make a variation, see if it still works, try another variation, and so on) and a simian typing pool's attempt at Shakespeare (random component substitution.) I blew up a lot of chips but became quite proficient at a few specific types of circuits that were useful in my music (if nobody else's).

The instruments I made shared a few defining characteristics. They could all be played: their sounds could be articulated continuously in "real time" (in other words, I didn't have to record them and then edit them on tape to achieve my musical goals.)

At the same time, they were difficult to control precisely—the sounds the au-

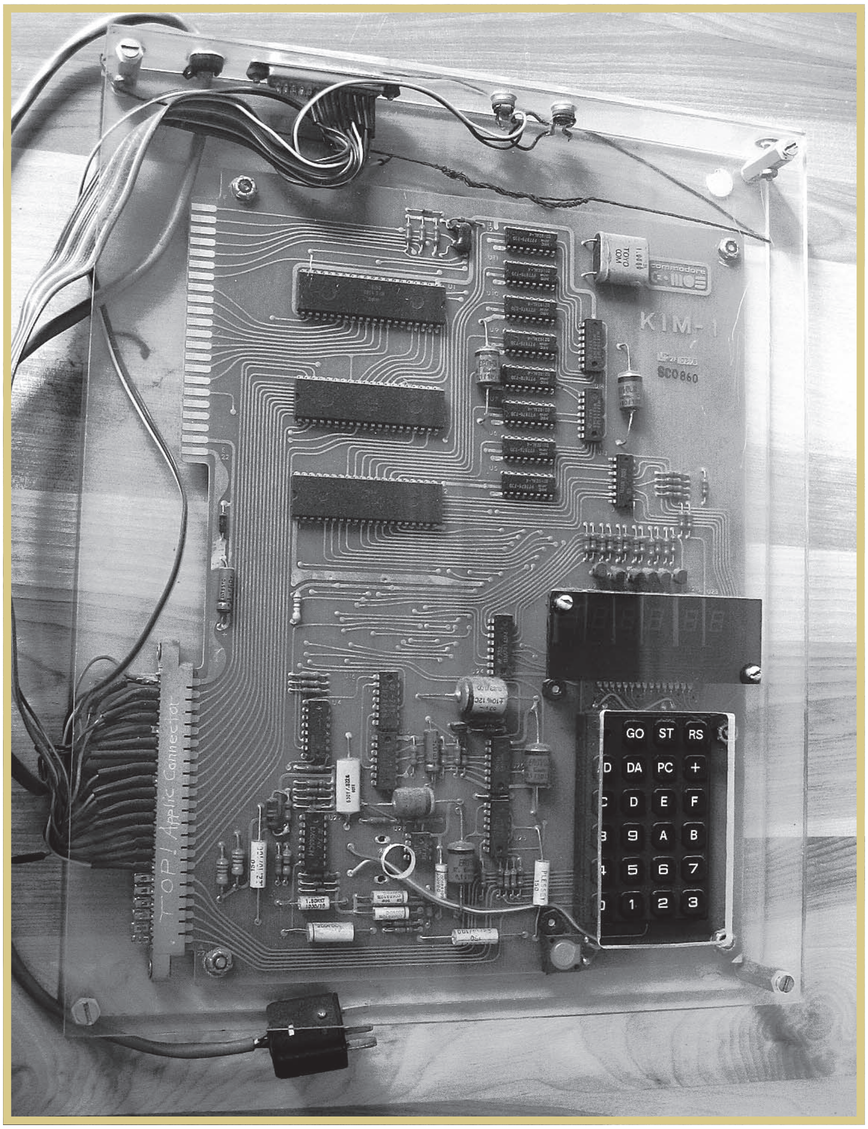


Figure 1. David Behrman's Kim 1 microcomputer. (image courtesy of David Behrman)

dience heard were the byproduct of the performer getting to know an instrument, rather than an articulation of a predefined result.

Finally, the instruments' behavior often reflected site-specific factors such as the acoustics of a room (the pitches and tempo of *Pea Soup*, for example) or the technology's essential properties or limitations: my "ensemble circuits," inspired by the coordination scores of Christian Wolff, only made sound when played by more than one musician. The four players in my 1978 composition *ANDS* played small keyboards that only registered players' actions if more than one player touched the same key on different keyboards at the same time; as a result, the piece unfolded in ways that were as surprising for the players as for the audience. (*Little Spiders*, an early work for a multiplayer computer instrument, is the closest composition to *ANDS* that is available on record.[6])

These instruments lent themselves best to musical strategies that favored some degree of improvisation and laid the groundwork of my early computer music. Just as acoustics determined the pitch world of my feedback pieces, the digital chips I used in my sound circuits suggested applying binary logic to the performer interface as well.

From soldering to programming

By the mid-1970s, the first affordable microcomputers came onto the market. Cajoled by the visionary Bay Area artist Jim Horton (http://leonardo.info/lmj/horton.html), a handful of electronic musicians (including myself) invested in the Kim-1—a single, A4-sized circuit board with a calculator-style keypad and a display glued on top (see Figure 1). Programming this thing in machine language and storing the program as fax-like tones on a finicky cassette tape recorder was an arduous, counterintuitive, headache-inducing process, but coding offered one great advantage over building circuits: it was easier to correct a mistake by reprogramming than by resoldering.

Moreover, even computers as crude as the Kim-1 had memory and could execute sequential logical operations. These features enabled the creation of instruments that could make ad hoc decisions based on past incidents, a feature of particular interest to those drawn to the quixotic unpredictability of live performance. Rather than simply giving more control to the composer, computers extended the interactive and improvisational possibilities of electronics. In my work (as well as that of my experimental colleagues), the computer began to embody elements of the score and player in addition to those of the instrument. (For an example of early interactive microcomputer music, see Behrman's *On the Other Ocean/Figure in a Clearing*.[7]) In the 1980s Apple, Commodore, Atari, and others introduced machines whose increasing sophistication and expanding software base gradually reduced the angst of programming, leading inexorably to the extraordinarily flexible and powerful machines and languages available today.

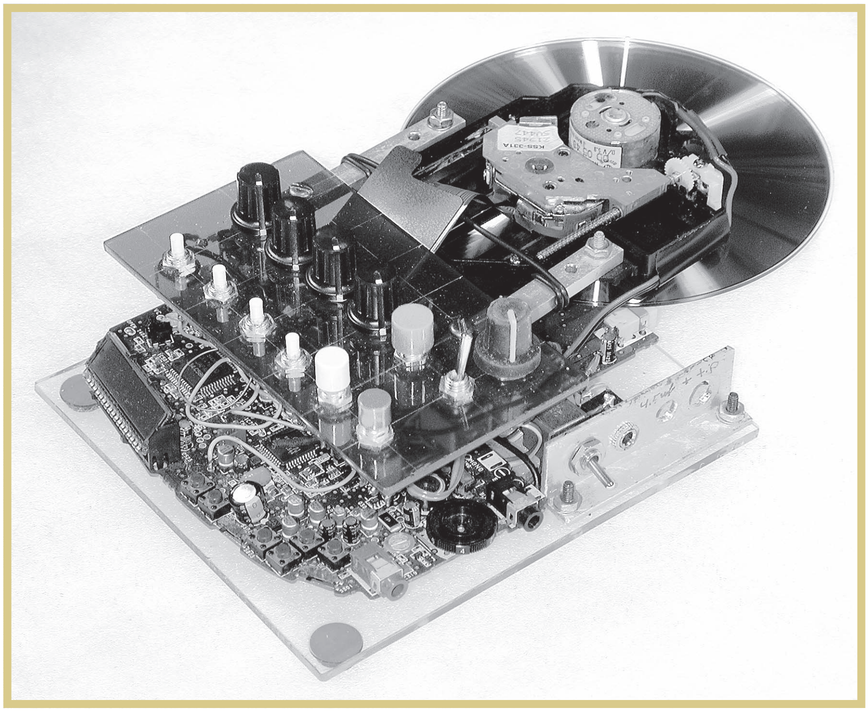


Figure 2. Sled Dog—a hand-scratchable CD player. I hacked this CD player so I could move the laser back and forth with my finger. (image courtesy of Simon Lonergan)

Homemade circuits faded into anachronism for most musicians, but I led a double life, still soldering even as I programmed. I found that a circuit or two hanging off the computer usually spiced things up a bit (see Figure 2).

I continued to produce what I thought of as "electronic music," even as the term itself became increasingly unfastened from either avant-garde posturing or the gritty notion of home-built circuitry. The cost of the synthesizer plummeted, its versatility grew, and by the early 1980s it had become ubiquitous in pop music. By the mid-1990s, computers had become as commonplace in music recording and production as they were in the office. As electronic instruments matured in an expanding marketplace, the idiosyncrasies and embedded scores of homemade circuits and artist software gave way to more flexible, widely applicable, generally useful devices.

By the end of the 20th century, electronic sound had become more than just commonplace—it was conventional, as natural to a techno producer whose musical roots lay in Kraftwerk as to me, an ex-student of the eminently un-danceable Lucier. Today, we choose to use electronic sound not to proclaim our musical ideology, but simply because we like it.

Regaining the power of touch

In 1999, I joined the faculty of the Department of Sound at The School of the Art Institute of Chicago. I discovered that my students had adopted the computer as an almost universal tool. They were adept at using their laptops to edit a video, compose a dance track, retouch a photo, lay out a poster, write a term paper, and design a Web site. Using the keyboard's command X and command V, they could cut and paste anything. But what the computer offered in the way of power and universality was obtained at the expense of touch.

These were artists, after all, and even the filmmakers and webmasters started out scribbling on paper. Many of them complained about the lack of immediacy and tactility in digital media, and in 2002 I designed a course to show my students some electronic alternatives to the computer—ways to bridge the gap between the sound world of a generation raised in an electronic culture and the gestural tradition of the hand.

My class handouts grew into a crude PDF textbook, which somehow escaped the walls of the school. Emails began to arrive asking me to conduct workshops, first in the UK, then all over the world (25 at the time of writing). Richard Carlin, an editor at Routledge, invited me to elevate my drawings and prose to a publishable state, and the result was *Handmade Electronic Music—The Art of Hardware Hacking*.[8]

Assuming no technical background whatsoever, my workshops (and the book) carry the reader through a series of sound-producing electronic construction projects, from making simple contact microphones, to transforming cheap electronic toys into playable instruments, to designing circuits from scratch. Along the way, I put the technologies into historical and aesthetic context through information about, and audio samples by, artists who have used similar devices to make significant musical breakthroughs.

I set out to regain the radical rethink of *Vespers*: to disassociate music and sound from the limited types of objects sold in music stores and, through this disassociation, to prompt new musical discoveries. At the same time, I wanted to explore how this drama of interaction between object and idea has played out in the experimental music of the past 50 years.

A roadmap to euphoria

The process begins with listening: making contact mikes and piezo drivers, experimenting with coils and tape heads, and using headphones and speakers as microphones. We lick our fingers and lay them gently on a radio circuit board: small currents flowing

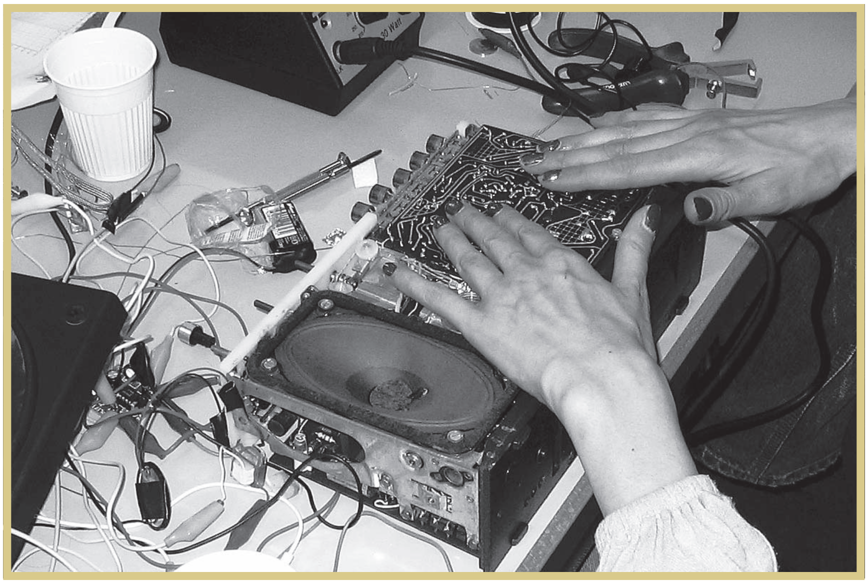


Figure 3. Laying of hands: A student plays the radio by direct skin contact with circuitry.

through the skin create feedback paths that tip the circuit into oscillation and transform the radio into a touch-sensitive synthesizer (see Figure 3). Alongside this radio project, I discuss the infamous Steim (studio for electro-instrumental music) "Cracklebox" from the early 1970s, which used this same idea of skin resistance to create an inexpensive electronic instrument whose expressiveness distinguished it from the keyboard synthesizers of the time.

We go on to open and rewire toys, and I describe the work of "circuit benders"—those who favor this approach to building new instruments with unpredictable musical results.[9] We misuse digital logic chips to build simple oscillators, distortion circuits, and gates and panners similar to those that the "Composers Inside Electronics" group made in the 1970s. As the project grows in sophistication, I discuss some of the "silicon luthiers," such as Bob Bielecki, who designed one-of-a-kind instruments for Laurie Anderson and other avant-garde musicians and artists. As we listen to video signals from cameras and games and hack LCD-based toys to create miniature pixel animations, I draw attention to "visual hackers," from Nam June Paik to Billy Roisz. We adapt game controllers for interfacing various circuits to computers to build alternative digital instruments. The workshops wrap up with "glue" circuits: simple mixers, amplifiers, and power supplies that can pull everything else together. By the end, the participant has acquired not only a wide range of electronic skills but also an appreciation of experimental methods in both the technical and aesthetic realms.

In selecting topics and projects, I reach back to my earliest days in electronic music. I try to remember what it was like to be completely incompetent, and—with the benefit of hindsight—what kind of advice and information would have helped me out of my jams. I select designs that are easy to understand and build, impossible to blow up, and suitable for mixing and matching to create complex networks from simple building blocks (like Legos)—a process facilitated by rejecting standard op-amp designs in favor of quirky circuits based on digital CMOS chips.

I stress "performability" throughout: the projects make extensive use of inexpensive photoresistors that change resistance with light, direct skin contact with the circuit board, pressure pads, and other intuitive, gestural interfaces. The pervasive aesthetic of cheapness and reuse prompted one student to compare my projects to clandestine prison crafts, such as shivs made from bedsprings. The projects set out to reveal types of manipulations and experiences that are fundamentally different from digital simulations and thereby inspire a different relationship to sound and to the material world of electronics. Having once opened up the sealed Pandora's box of a handheld game, people are, I find, oddly empowered: they realize the contingency of things that had seemed fixed or beyond their control or intervention.

In every workshop there's inevitably this beautiful moment (usually around the time the students discover the ticklish spot that causes the radio to swoop and warble) where euphoric self-confidence sets in. They leave happy, fearless, and an obvious threat to the electronic possessions of their roommates, spouses, and children. I designed the syllabus to be a roadmap to this euphoria, and to suggest that euphoria can have a higher calling: it can be used to make music and art. It has happened in workshops around the world: a happy techno producer starts off merely wanting to add something new to his or her sound pallet, only to finish up making "sound art" and tracking down obscure recordings by the artists we've discussed.

Understanding post-digital physicality

Developing the projects was not simply a matter of foisting the designs of my youth into today's broader aesthetic climate. The technology itself has changed as well. Thanks to the recent introduction of rubber paint ("Plasti-Dip"), we can waterproof a basic 1970s-era contact mike (a piezo disk wired to a guitar plug) for use as a hydrophone. Even the simplest of electronic toys today contains a sample-playback computer, whose clock speed can be adjusted by adding a potentiometer or photoresistor, allowing the most inane of barnyard sounds to be slowed down into a spookier, more musically interesting range. Out of cheap handheld computer games come LCD screens that can be transformed into crude video projectors. And the pressure to increase battery life in cell phones and other portable devices has made low-power components so ubiquitous that most hacking can be done with batteries—cheaper, quieter, and much safer than the power supplies needed 30 years ago. Some of these changes are merely practical; others imbue an instrument with a character distinctly different from its 1970s ancestor.

I acknowledge the proliferation of electronic sound today, and I've tried to appeal to the electric guitarist, VJ, location sound recordist, and card-burning experimentalist alike. At the same time, I can't deny that I bear an avant-garde bias. I adapted most of the projects from the work of musical colleagues, not Intel Application Notes, and I make the point that these tools are best understood in the context of the music those artists made with them.

Moreover, I am keenly aware of the ephemeral nature of the field of live electronic music—usually un-scored, frequently unrecorded, and in general poorly documented. I try not only to perpetuate the craft of handmade electronic instruments but also to build up a documentary record of significant music made with them. Despite the awareness within musicology of the profound effects of instrument design on the development of musical forms and composition, *Handmade Electronic Music* is the first book to have linked the making of musical circuitry with critical listening to extant electronic music, or to the history of the field.

I sense that we are in the midst of a major surge of interest in *post-digital physicality*. I see and hear circuits from the book on YouTube (www.youtube.com/watch?v=fKtT4BoZSO0). Web sites ranging from collections of vintage schematics to empirical suggestions from circuit benders proliferate (www.deviantsynth.com, www.getlofi.com). The recent rise of laptop ensembles—such as the Princeton Laptop Orchestra (http://plork.cs.princeton.edu) and Powerbooks Unplugged (http://pbup.goto10.org/pbup.html)—has been paralleled by the emergence of circuit bands (see http://okno.be/old/xmedk/INSTALL/toysband.html). My workshops and book can be seen as a bellwether or catalyst—take your pick.

Making the connection

As long as I've been making music, I've been making music with electricity, and, from the start, this music has required connections. Instruments, tape recorders, circuits, and amplifiers all needed to be hooked up to one another before I could hear a sound. I found that the more interconnections there were, the better things sounded. A guitar was duller without a fuzzbox, and it was even shinier with tape echo, feedback, and a squealing oscillator thrown in. Electronics, like the nature that spawned them, abhor a vacuum, and circuits seem more interesting in groups than alone.

The 1970s were a good time for socially active circuits. It was the heyday of analog synthesizers, festooned with patchcords. Tudor's sprawling matrices of small boxes resembled ant colonies more than musical instruments: with numerous interconnected pathways, they evinced a mysterious collective behavior that went beyond the understanding or control of their solo human performer. Any individual circuit might have been relatively simple, capable of only a narrow range of sounds, but the multiple lines of signal flow and feedback contributed an inherent instability, such that one small nudge of a knob or flick of a switch could propel the array from dead silence to complex, self-perpetuating rhythms.

My first microcomputer seemed so sophisticated (and expensive!) that I was tempted to hook it—and it alone—up to a speaker and let it sing its aria. And so I did. For exactly one piece. A disappointingly flat piece, performed once and only once, in 1978. Then I was back to adding wires and introducing my computer to other circuits, instruments, and sundry objects.

Today, with many musicians in the thrall of "laptop music," my laptop sits on the stage wreathed by several years' accumulation of musical flotsam. Despite the power of a single modern computer, and the myriad "virtual interconnections" possible with software plug-ins, there's no substitute for real jacks and plugs. It's as though, with quasi-homeopathic spookiness, the very passage of electrons across the infinitesimal gap between plug and jack affects the sound.

All of this should come as no surprise. In general, ensembles produce richer results than soloists; the interaction of a group of players is hard to approximate on a solo instrument. Circuits, like improvisers, tend to follow the logic of "the wisdom of crowds," described by James Surowiecki:

> *If you ask a hundred people to run a 100-meter race…the average time will not be better than the time of the fastest runner… . But ask a hundred people to answer a*

Electronics, like the nature that spawned them, abhor a vacuum, and circuits seem more interesting in groups than alone.

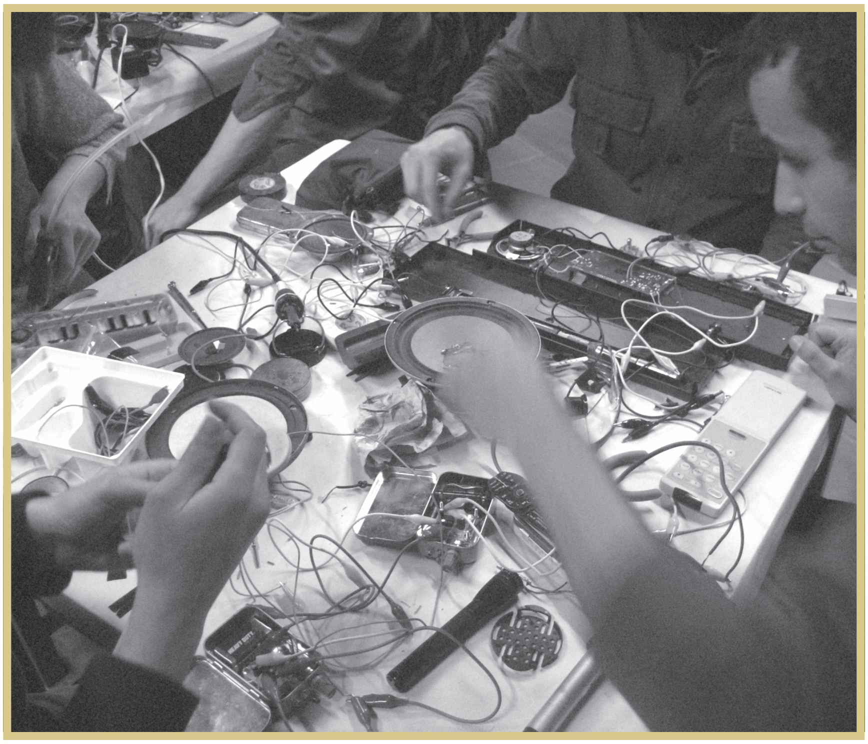
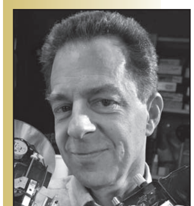


Figure 4. ***A Turn in the Shrubbery*****: live performance/installation by members of my hardware hacking workshop in Bogotá, Colombia (Oct. 2007).**

question or solve a problem, and the average answer will often be at least as good as the answer of the smartest member. With most things, the average is mediocrity. With decision making, it's often excellence. It's as if we've been programmed to be collectively smart.[10]

Music is not a 100-meter race but a series of decisions. And circuits, like people, seem to be inherently "collectively smart," even those that might individually be rather plodding. My workshops in hardware hacking end with an event I call *A Turn in the Shrubbery*. We fill a gallery, lobby, or bar with tables, each with its own small amplifier and speaker; then participants (as many as 25) set up in groups of two or three around the tables. Some "perform" on the instruments they've made in the course of the week, while others solder on until closing time, occasionally testing their evolving circuit through their speakers (see Figure 4). Part installation, part performance, part social ritual—the resulting din is unlike anything else I've heard. After five days of hacking circuits, none of the participants can claim to be an engineer, but collectively they are very smart indeed.

the AUTHOR



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