TECHNOLOGICAL CHANGE:

The Challenge to the Audio and Music Industries*

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When we currently think of high technology in the audio and music industries, we think of digital (electronic) technology. But this digital technology has matured only in the past few decades. What are some new technologies that might supplant digital technology? More importantly, to what extent will our industry and Society take a leading role in how those new technologies develop?

0 INTRODUCTION

In public talks about audio, one often sees a timeline in which "major changes in the audio industry" are said to occur every 10, 25, or perhaps 50 years. Rather than searching for periodicity in a one- or two-dimensional timeline, in this article it will be more helpful to start out by enumerating some of the multidimensional axes along which change occurs. One axis would be the number of channels of audio: mono, stereo, (aborted) consumer quad, and now multichannel (possibly encoded). Another would be the axis of storage technologies, starting with direct mechanical recording (Edison), moving to analog magnetic recording on tape (allowing cutting and splicing) through digital magnetic tape to the point of the digital CD and the DVD. Another axis represents the methods for transmission: electrical (Bell and Morse), electronic, and digital. Yet another axis would be consumer, semi-pro, and pro. There are many other axes. On any given axis, change is often motivated not by developments within the audio industry but instead by changes in technology outside. The audio industry can hardly be said to have driven the development of the vacuum tube, for example, or of digital signal processing chips. These changes outside the audio industry happen on an irregular basis in time, and each change typically affects an idiosyncratic subset of axes.

This article looks at some of the influences coming from outside the audio industry. The emphasis here is not on buzz words such as DVD, object-oriented programming, multimedia in the corporate PC, the Java programming language, censorship on the Net, set-top boxes, the cable industry versus the telephone company, and the like. Also, the goal is not self-indulgent crystal-ball gazing as an end in itself. Rather, it is time to anticipate what might change in the technological world around us, to inspire us to reflect on what action our industry and Society might take.

1 COMING CHANGES IN TECHNOLOGY: NETWORKS AND BUSES

Before tackling the future, let us look at some up-and-coming outside influences on the audio industry. These are technological developments from the computer industry that will affect the audio and music industries. When I was invited to give the keynote address at the AES 101st Convention, I had just returned from the April 1996 Winhec, the Windows hardware engineering conference sponsored annually by Microsoft. What I heard and saw there impressed me so much that the first heading to enter the outline for this talk was the heading for this section. The reason is that no less a market force than Microsoft is pushing even the hardware manufacturers of personal computers to change in ways that also affect our industry. This section covers those changes, and some other related changes as well.

1.1 Universal Serial Bus

The Universal Serial Bus (USB) [1–3] was designed by a private consortium (NEC, Intel, Microsoft, Compaq, Digital, Northern Telecom) to replace the many connectors and cables on the back of a PC (Fig. 1). Running over a cable, USB appears to be a network, but is in fact just a cable implementation of a serial bus. With a maximum cable length of 5 m, a maximum of 7 cables in any path, and a maximum of 64 devices on one bus, it is clear that USB is intended for peripherals clustered around a single PC tower instead of, say, for wiring an entire building.

One marketing goal for USB is to

mouse	game controller
keyboard	phone/answering machine
monitor	audio devices
disk drive	scanner
modem	glove
ISDN	set-top box
CD-ROM	DVD

Fig. 1. Typical devices to be connected to a personal computer via the Universal Serial Bus.

*This is a written version of the keynote address presented at the 101st Convention of the Audio Engineering Society, Los Angeles, 1996 November 8-11.

have one connector on the back of the PC to handle all peripheral devices. Another marketing goal is to extend the plug-and-play concept to devices outside of the backplane inside the PC. USB devices can be hot-plugged, that is, a new device can be inserted onto the bus while the PC and bus are running. The bus then reconfigures itself appropriately. This is a major improvement over the traditional PC, where installing a new device entails powering down the PC and opening the PC case. There must be one (and only one) bus master. Given the close participation of Microsoft, it is no surprise that the bus master must run Windows. The cable has four wires of which two carry data and two carry power, so some devices could draw power from the bus. NRZI coding minimizes electromagnetic interference.

There are provisions for both asynchronous and isochronous delivery of data. In practice, time-critical transmission, such as delivering the next audio sample, can happen in the isochronous part. In fact, transmission of audio over USB has been demonstrated [4].

There is no royalty for using the bus. At the time of the AES 101st Convention in November 1996, personal computers implementing USB were on the market [5]. Since many audio and music professionals use personal computers in their daily work, we can expect portable PCs with USB connectors to appear very soon in studios, performing venues, and the like. Installing USB-equipped peripherals such as monitors and loudspeakers in such locales may become the norm.

1.2 IEEE 1394

Like USB, IEEE 1394 is a serial bus. It was originally the brainchild of Michael Teener at Apple [6] and has been ratified as an IEEE standard. (Historically this bus has been called "Firewire.") Development of the standard is now carried out by the 1394 Trade Association [7]. The EIA R-4.1 Standards Committee has selected 1394 as the digital video interface of choice for both point-to-point and multipoint consumer electronics interfaces for the United States. There is talk of 1394 being used for set-top boxes and a 1394 "in-home network."

There are backplane and cable implementations. As with USB, there is provision for asynchronous and isochronous transmission. The 1394 bus also carries power and data in one cable. Since 1394 is significantly faster than USB (200 Mbit/s or more), certainly many channels of AES/EBU at the usual sample rates if not all 56 MADI channels can be accommodated. With a cable length starting at tens of meters, and with fiber-optic extensions in the works, wiring large venues and buildings becomes possible.

There is an extensible data packet that can be carried synchronously, which allows time-critical data (such as audio) to be carried in a wide variety of formats—even those developed outside of 1394. Working with the 1394 Trade Association, Sony and others have created a proposal for carrying AES/EBU packets and MIDI over 1394 [8]. As this article goes to press, this proposal is being ratified by the A/V working group of the 1394 trade association.

The 1394 serial bus shares with USB the ability to hot-plug devices. However, 1394 does not expect a designated bus master. Instead, the entire bus configures itself on power-up. When needed after a new device is inserted, a new bus master is selected automatically. Standards are also in the works to adapt this capability to the needs of the audio and music industries [9] which would be a boon for live and studio applications. New devices can be plugged in as the need arises, and the "network" does not stop working when one connector or device or cable goes bad (a situation all too familiar on-stage).

1.3 Microsoft and the PC

In his keynote address at Winhec mentioned earlier, Bill Gates paid significant attention to digital audio in the PC. Gates's plea for "please no more PC plug-in cards" drew loud applause. There were talks at Winhec about 2-d audio, 3-d audio, and real-time audio over the internet. What is surprising here is that an operating system vendor is pushing to expand audio capabilities. There was even a demonstration of digital audio transmission over IEEE 1394 in Gates's keynote, using a 1394 digital audio node developed by PAVO.

In the same keynote, Gates introduced the idea of the "simply interactive PC" (SIPC), which would also simplify our day-to-day work. The basic idea of SIPC is to make the PC an appliance, possibly suspended in a low-power waiting state after a certain length of time, but always immediately available. Compared with turning on a consumer product such as a toaster or a CD player, turning on an IBM-compatible personal computer is currently a vexing process: it takes the PC a long time to power up; the PC displays cryptic messages such as BIOS calls; the PC goes through long procedures such as memory tests.

A SIPC should fix this. It should also be like an appliance in that the consumer does not open it. The case is sealed: you don't set switches inside, you don't install cards inside. An enabling technology for this concept is the serial buses mentioned above. The user connects devices to the PC through USB or 1394 instead of powering down and opening the case. In other presentations at Winhec 1996, Microsoft made it clear that its operating systems will support both 1394 and USB. Indeed, a hardware manufacturer will need to include USB to be given "PC 97" compliance certification by Microsoft. Thus, 1394 and USB should have unified hardware and software support when they appear on the market.

One might argue that what is discussed here is merely a consumer development. I predict that these developments will quickly work their way into professional audio and music situations.

1.4 Ethernet

This network was first developed in the computer industry and is now quite popular for connecting PCs, mainframes, portable computers, workstations, and other computing devices. Ethernet is used as the backbone for several academic [10] and commercial audio control systems, such as QSControl from QSC [11] and HCA from Harman/Soundcraft. Ethernet has not yet found widespread acceptance for delivering digital audio because of an inherent design limitation: there is no upper bound on the maximum delay between sending and receiving transmitted data [12]. A recent improvement in this situation is Cobranet from Peak Audio [13, 14], which can provide isochronous service at 100 Mbit/s over Ethernet.

1.5 Other Developments

It would exceed the scope of this article to discuss other well-known technological developments, such as audio transmission over FDDI [15], or the rapid changes in the technology for distributing music and audio [16, 17]. The point should now be clear that the computer industry is already exerting a profound effect on how we connect devices for storing and modifying sound, and how we transmit sound between those devices. It is worth noting that many of these developments have occurred outside the traditional audio industry.

2 FUTURE CHANGES IN TECHNOLOGY

We turn now from technologies that are poised to exert a profound influence on the audio industry to those technologies that are just beginning to exert their influence, or indeed are just beginning to be developed.

2.1 Micromachining

2.1.1 Definition

Micromachining is the art and craft of sculpting three-dimensional stationary and moving objects with dimensions on the order of micrometers. Since silicon is one of the materials most often employed, the term silicon micromachining is sometimes used to describe this process. Micromachining is distinguished from microelectronics, meaning the production of analog or digital circuits on the same order of magnitude [18]. Just as digital signal processing for audio and music benefited enormously from advances in DSP for military applications, micromachining was given a starting boost by developments in microelectronics, which had developed techniques for chip manufacturing, miniaturization, photolithography, clean-room work, growing silicon wafers, and the like. Micromachining originally concentrated on creating small three-dimensional structures, possibly with moving parts. More and more, electronics have become associated with the microstructures. Now there is a full-scale movement, with its own journal, for micro-electrical-mechanical systems (MEMS). A MEMS device has electrical and mechanical components manufactured together on the scale of microns.

For a rather playful example of the size and complexity possible with micromachining, consider the car model (Fig. 2) built on the scale of 1:1000 by a team at Nippondenso [19]. The white blobs in the figure are actually grains of rice. Fig. 3 shows the parts that went into the construction. The body shell (30 μm thick) was made in two halves by molding and casting. The tire has a diameter of 0.69 mm, is 0.17 mm wide, and is made from brass. The chassis is 4.68 mm long, 1.09 mm wide, and 0.5 mm high. The researchers assembled a micromachined motor, and the car runs! The fastest speed is about 100 mm/s. The researchers report that the car could have gone faster, but the tether wires providing power slowed it down.

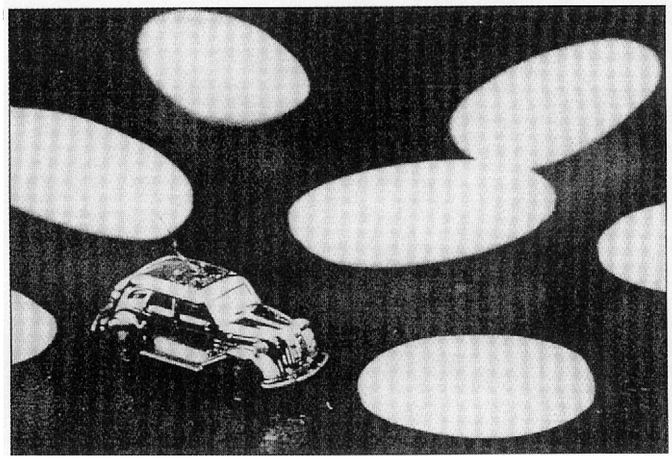

Fig. 2. A micromachined car and rice grains [19].

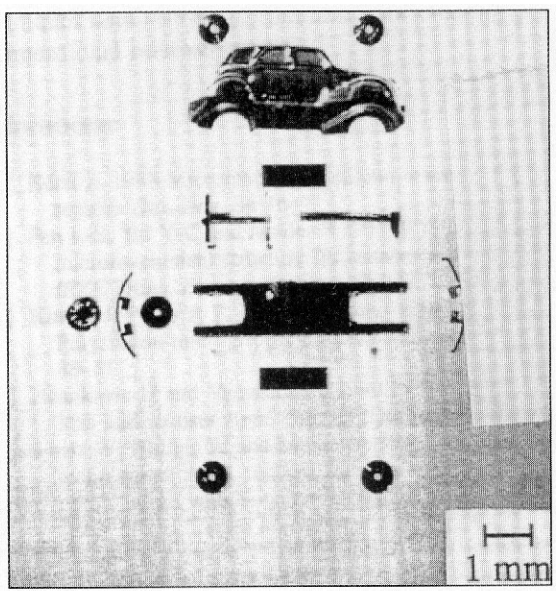

Fig. 3. The parts for the car shown in Fig. 2 [19].

2.1.2 Market

The first major application of micromachining was for motion and pressure sensors, such as in automobiles [20]. There were about 25 million micromachined sensors manufactured and sold in 1994 [21, p. 18]. Markus et al. [22] predict that the market for these sensors will grow by 10–20% annually, reaching more than $8 billion by the year 2000. Swyt [21] is even more optimistic, predicting $14 billion by the end of the millennium. No matter which figure one believes, it is clear that the market for micromachined sensors is large. Originally the terms sensor and actuator were widely used in the field, but both have now been supplanted by the term transducer, which we know and love.

2.1.3 Basic Technologies

How is a typical micromachined device manufactured? We start with a simple demonstration of etching silicon. As mentioned, silicon is the main material used for a micromachined substrate, although other materials can be and are used. Silicon has many advantages: low density, high melting point, great strength.

The basic idea is shown in Fig. 4. In A, an etch

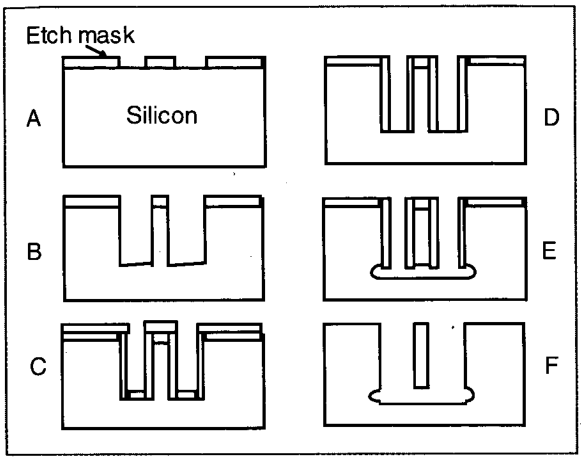

Fig. 4. Micromachining a suspended beam (cross section) (after [23], p. 103).

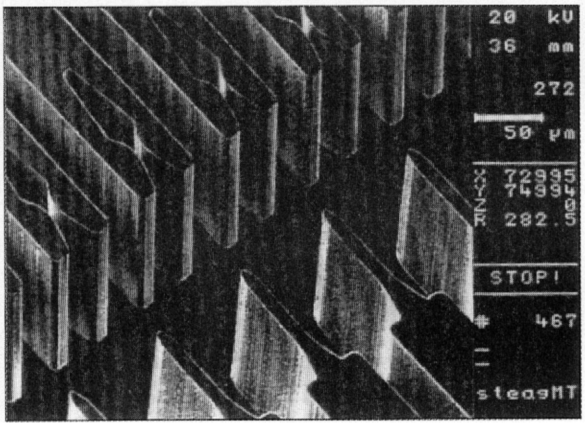

Fig. 5. Microconnector tips made with LIGA [25].

mask of silicon dioxide is deposited on a silicon substrate. In B a gas mixture etches downward but not sideways, leaving most of the material below the photoresist. The etchant is anisotropic because it follows the crystal orientation of the substrate [24, p. 46]. (One discusses the diffusion rate of the etchant in terms of angstroms per minute.) In C, the walls and roof are covered with another photoresist. A different etchant in D takes away the outer horizontal masks, leaving the two valley floors exposed. Yet another etchant releases the middle column in E. In F, all the masks are removed. If one now considers Fig. 4 to be in cross section, the isolated part of F is a cantilevered beam. Later, other substances may also be applied to the perimeter of the structure, such as a magnetic coating which can allow part of the structure to react to electromagnetic fields.

This silicon etching technique has the disadvantage that it is hard to create truly deep structures or structures with fine detail. The LIGA technique developed in Germany (the name is the German acronym standing for Lithographie, Galvanoformung, Abformung, punning on the German word for "league") is suited for what is termed structures with a deep aspect ratio. LIGA can also be used to make molds for injection molding. Fig. 5 shows microconnectors 180 μm tall developed for use in an endoscope. Note the deep straight walls, which are almost a cliche in this technique. One disadvantage is that the original LIGA technique requires synchrotron radiation, but alternatives are said to be in the works.

Yet another method uses excimer lasers [26]. Since this kind of laser removes material without heating it, some materials such as organic compounds can be more easily machined.

One can easily imagine that hybrids of these techniques are used. For example, two different parts can be made with two techniques, then the layers can be laminated together. Cavities can also be created in this way. There is even a cell library of elements called the Consolidated Micromechanical Element Library (CaMEL) which works inside a standard publicly documented micromachining manufacturing process supported in part by government funding [22, 27].

2.1.4 Specific Audio Applications

Given the above discussion of transducers, sensors, and actuators, it should come as no surprise that these techniques have been exploited to manufacture microphones [28, 29]. The initial market is for truly miniature microphones, such as those needed for portable telephones or hearing aids.

Although I know of no explicit audio applications for such structures yet, the development of microresonators is intriguing for the audio industry. The resonator shown in Fig. 6 [23] was developed for studying mechanical losses, which does not concern us here. In the figure, the resonator is the white structure in the middle. There are fixed electrode combs on the left and right that mesh with the moving electrode combs in the middle. The entire moving part of the structure has been released from the lower substrate. The dark line to the right of the figure is 50 μm. The ➥

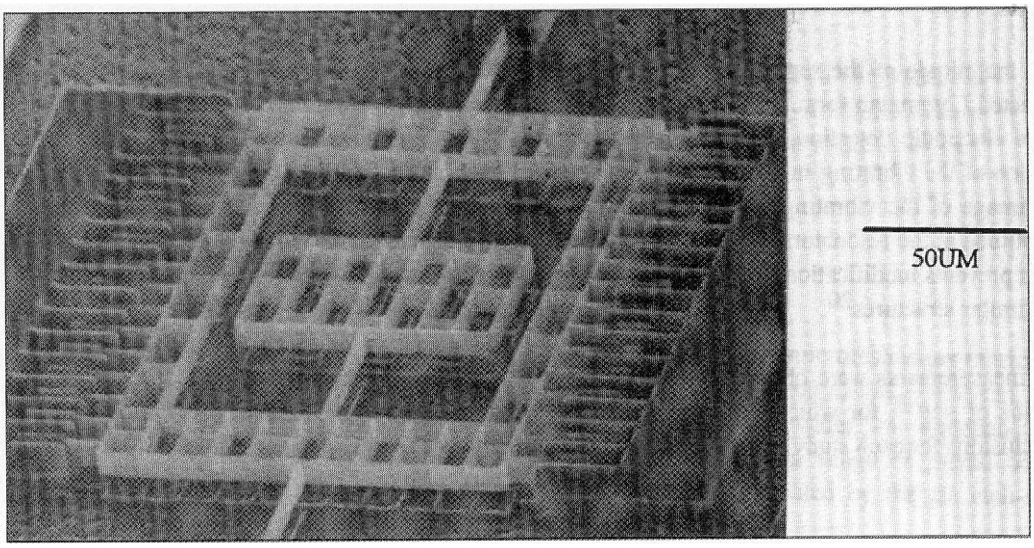

Fig. 6. Micromachined resonator [23].

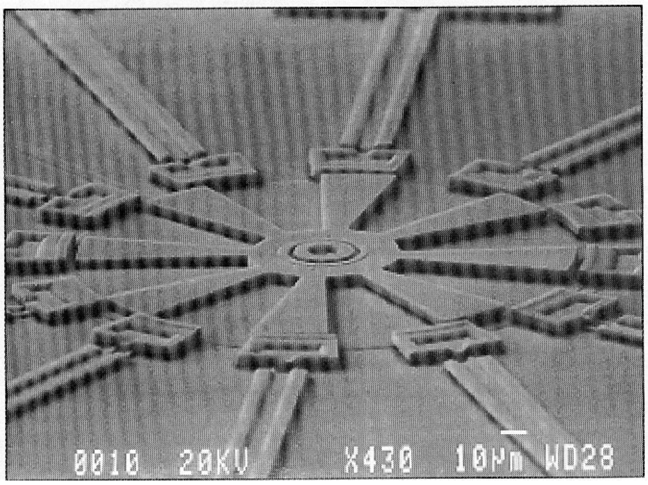

Fig. 7. Micromachined motor. White horizontal line: 10 μm. *(Courtesy MCNC MEMS Technology Applications Center)*

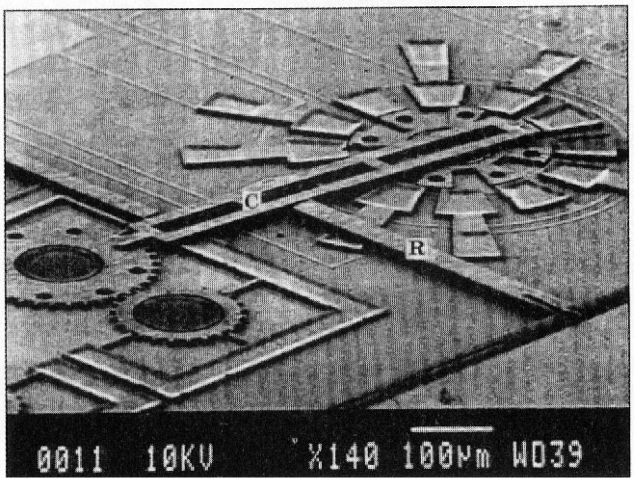

Fig. 8. Micromachined motor moves the gear [31].

beams in the resonator are typically 5–6 μm high and ¾ μm thick. The edges of the electrodes have been covered with metal. If appropriate electrical fields are applied to the fixed and moving electrodes, the resonator rotates about the beam that goes from the upper right to the lower left in the figure. The mass in the middle is for inertia.

2.1.5 More Examples of Structures

Fig. 7 shows a typical micromotor taken from the CaMEL library [30]. There are 12 stators to which power is conducted through the horizontal channels. The rotor has eight poles and is lifted off the substrate surface using a variant of the etching technique presented above. The motor rotates around the hub, but is of course separated from it.

Gears and motors such as those shown in Fig. 7 have been in existence for some time. The question remains how to get such motors to do useful work. The problem revolves around creating a structure strong enough, yet flexible enough, to transfer energy from the motor to another device. One solution is to fabricate a beam separately from the motor, then join the two [31]. In Fig. 8, the motor is in the upper right corner, joined by a beam to the gear chain in the lower left corner. The rotors, gears, and beam are 5 μm thick. The restraint (labeled R in the photograph) is needed during fabrication but is removed before the device operates.

More recent work has turned to building microrobots, inspired in part by the mechanical design of insects. This technology is still in its infancy. The fundamental building blocks are now being researched, designed, and constructed [32], but as far as I can determine no sophisticated robot in the usual sense of the word is finished yet. Fig. 9 shows a set of such fundamental building blocks including a hollow triangular beam (HTB). An unassembled HTB is in the bottom center. The plates of an HTB are joined by micromachined hinges and snaplocks. During assembly, micromanipulators lift two of the plates up and over the center plate to create the beam. Although not shown here, HTBs can be manufactured [33] such that they rotate and stand upright. A stepper motor connected to a ➡

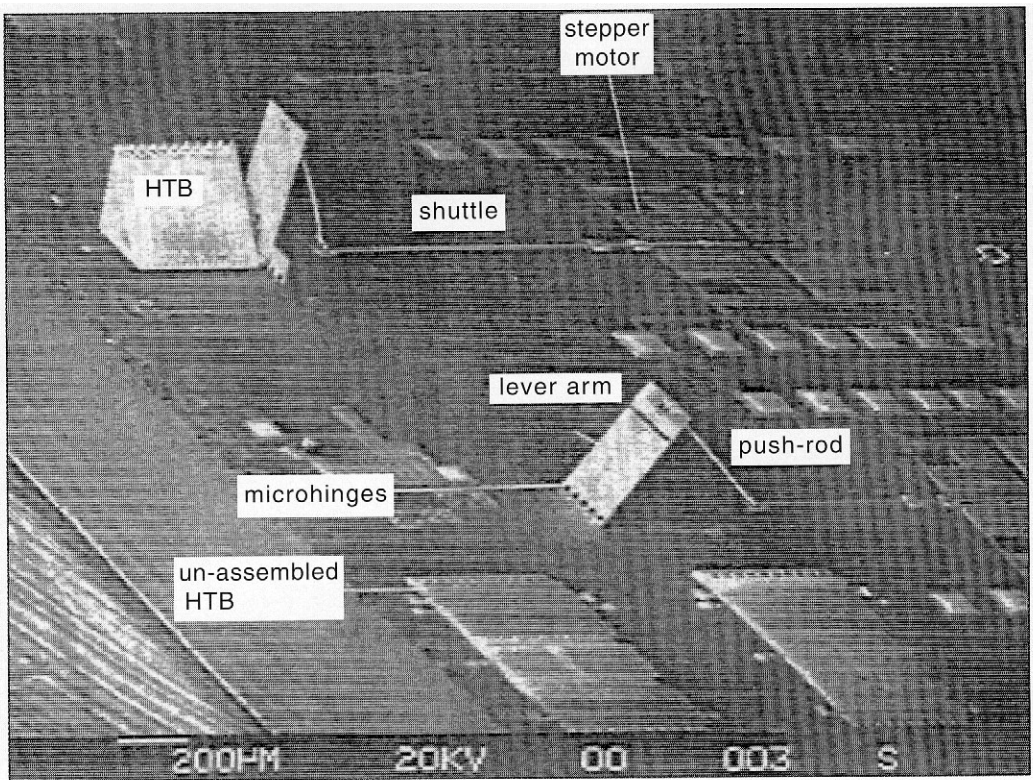

Fig. 9. SEM of robotic test structures [32].

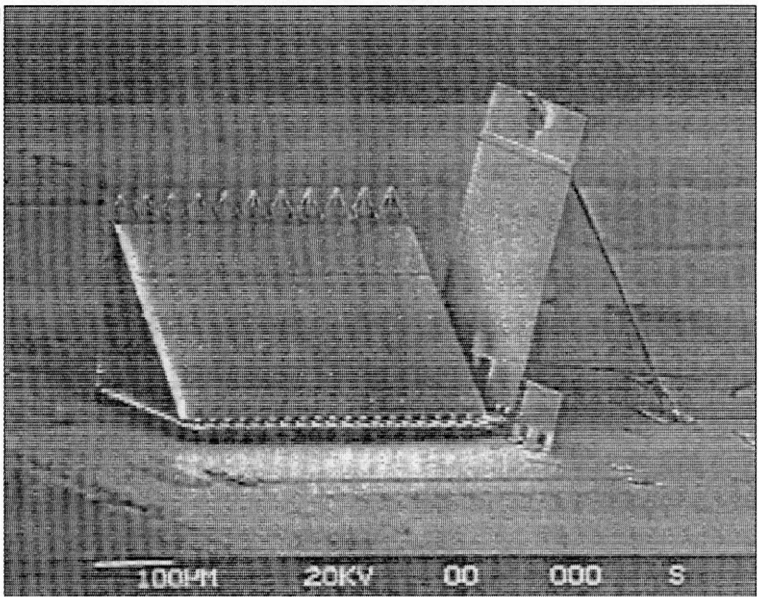

Fig. 10. Lever arm coupled to a hollow triangular beam [32].

pushrod provides the force to move the structures. Fig. 10 shows a close-up of an HTB. The hinge can be seen at the bottom juncture, and the snaplock is at the top. The idea is to connect many such building blocks through articulated joints to create the equivalent of robot arms and legs. As a first step, a gripper and a basic hand [34] have already been constructed.

2.1.6 Other Uses of Micromachining

Micromachining is being investigated and used for such diverse applications as pumps for microdosages of drugs, microvalves [35], thermometers, thermocouples, thermostats, ink jet printers, fuel-injector nozzles, microrelays, hinged mirrors, and gyroscopes. Given the already existing large market forces behind this technology, and given that it is already starting to make inroads into manufacturing of audio devices, we can reasonably assume that this technology will affect the audio and music industries in the future.

2.2 Nanotechnology

2.2.1 What is the Scale?

As this discussion progresses from micron-scale devices to a much smaller scale, it is important to remember that we are not interested in miniaturization per se, but rather in developments outside our industry that may later affect us. Keeping that emphasis in mind, we now move to miniaturization at the level of atoms and molecules. This is clearly new territory: the term micron is common in our language, but "nanon" is not yet.

2.2.2 Definition of the Field

There is a broad spectrum of work at the nanon scale. One pioneer in the field might prefer the term molecular nanotechnology, in which molecular manufacturing is the construction of objects to complex atomic specifications using sequences of chemical reactions directed by nonbiological molecular machinery [36, p. 1]. Another view of nanotechnology is given in this definition: the projected ability to use positional control of chemical reactions to build complex materials and devices (including molecular machinery) resulting in precise control of the structure of matter at the molecular level [37, p. 173]. Materials created in this manner, or devices built from such materials, are called eutactic. The term mechanosynthesis also refers to this positional control.

2.2.3 History of the Field

One starting point of the field is a lecture given by Feynman [38] in which he postulated miniaturization well beyond anything commonly imagined at the time. The first major technical reference is [36]. Much of the work remains at the level of intriguing speculation and (very thorough) paper designs. An interesting and lively discussion is given in [39]. Research is conducted at various centers including IBM [40], Xerox PARC [41], and the Foresight Institute [42] founded by Eric Drexler.

2.2.4. Techniques for Implementation

How do we assemble matter to specification? One approach is the mechanical one, assembling matter by placing atoms where desired. This has been demonstrated in the last decade with tunneling microscopes, which can deposit individual atoms onto a substrate. The control is precise enough that words and letters can be formed [43], making the smallest written works known to humanity and demonstrating a level of control over atomic structure once thought impossible. One can envision other kinds of hands or grapplers that move an atom or molecule to a desired location. Remembering that micromachining is a different field at a different order of magnitude, one can even envision that micromachined structures would be appropriate for this work. Or, if a liquid is the result of precise placement of atoms and molecules, then we have an new kind of chemistry in which reactions no longer happen merely through diffusion.

Biological organisms are adept at breaking apart compounds in their environment, then synthesizing new molecules from the raw components. It is easy to imagine an artificially created enzyme that can break apart a molecule into its constituent atoms, and other enzymes that create a three-dimensional structure from atoms and molecules.

2.2.5 Applications to Audio?

How could we use this for audio? An increase in computational capability due to increased miniaturization is the obvious first answer. Nanotechnology might provide new computational machines as well. Of course industries outside of audio are also interested in this. Phelps [44] quotes a NASA source as saying: "Some forms of nanotechnology appear to have enormous potential to improve aerospace and computer systems. Computational nanotechnology—the design and simulation of programmable molecular machines—is crucial to progress."

Drexler worked out a thorough design for a nanocomputer, in which moving molecules allow the representation and manipulation of information. A sliding rod with protrusions can implement basic logic functions. In [36] there are designs for combinatorial logic. Drexler foresees a CPU-scale system containing 10^6 transistor-like interlocks fitting within a 400 nm cube. Bill Joy [45, p. 276] takes the step beyond a general-purpose computing engine made possible by Drexler's ideas. Instead of designing a very fast or massively parallel computer, you design a computer to solve a particular problem. In other words, you compile a computation engine instead of compiling a program to run on a computation engine.

Another major area of potential change is in materials science. I believe that materials science research with nanotechnology might help solve a longstanding problem: how do we minimize the difference between a recording of a sound source and the original? Nanotechnology may provide us with new materials, be it for magnets, loudspeaker enclosures, paper cones, or whatever, that will help solve this question. Again, we are not alone in our interest. Pinneo [46] talks about growing diamond and industrial uses for diamond. Drexler [37, p. 9] sees major advantages for materials produced with nanotechnology: a perfect material such as diamond leads to a stronger structure; raw material is not wasted during manufacturing, meaning lower energy and material costs; the finished product weighs less. Other envisioned applications of nanotechnology (increasing longevity, eradicating disease) and sociopolitical ramifications (a workless society) are not discussed here, not because I wish to avoid the inherent controversy but because they exceed the scope of this article.

2.2.6 Is it Feasible?

There have already been demonstrations of the feasibility of some of these ideas. Creating nanodocuments was mentioned above. Nanostructures can be built using techniques reminiscent of micromachining [47]. Molecules have been created that can, among other things, assemble themselves [48]. Recent work shows that the orientation of self-assembling structures can be partially directed by electric fields [49]. There are now wires that are a few atoms wide and up to 10k Å long made from molybdenum and selenium encased in plastic [50].

2.3 Biological Computing

Let us now abandon the temptation to explore even smaller physical scales (such as subatomic assembly) and turn to novel techniques for computation. Library research into computational aspects of biology quickly leads one into areas such as the human genome project and some forms of nanotechnology. (Some researchers in our field have also used genetics-inspired algorithms [51, 52].) But in this section I am concentrating on using biological techniques and processes to solve a problem computationally.

Let's look first for parallels between today's computers and certain biological processes. Bray [53] points out that some proteins respond to inputs as diverse as temperature, light, voltage, or a mechanical force. A protein can generate light, create a molecule, or cause physical motion. Proteins can also in effect create the weighted sum of their inputs. Living cells often amplify stimuli in their environment or adapt to them. In a large sense, all of these functions are common enough in the technology prevalent today in our field. Beyond these analog functions, Bray points out that in theory protein molecules may carry out logical operations. For example, there are ion channel structures in the plasma membrane. A channel may switch rapidly between one of several distinct states. Citing other researchers, Bray concludes that flip-flop-like behavior can be achieved. There is even an analogy to selfmodifying code here. Some enzymes can modify a class of proteins that includes the enzymes themselves. Under the right conditions, the enzyme becomes irreversibly active, even when the concentration of ions needed to start its action is reduced.

Biology-based computation might also turn out to be useful for solving problems requiring high levels of parallel processing [54]. Where do we perform highly parallel processing in the audio industry? One place is of course inside the cochlea of the ear. Another is in higher level processing of nerve signals from the ear. Finally, I think of systems in which loudspeaker equalization is continuously adjusted during performance. Such systems are now in the field, but might be improved by inexpensive parallel processing.

What keeps current technology from performing massively parallel processing? As a programmer I find that the design of the central processing unit (CPU) of most current computers remains very conservative in many respects. One of these is the manner in which the instruction stream is processed. Almost all CPUs today operate on one instruction stream at a time, even if they operate on many instructions per second. Only in the case where specific hardware is dedicated can several streams be processed at once [55-58]. I know from personal experience that at least some of these devices are a challenge to program, since they are also often highly pipelined.

As a first step toward parallel processing using biology, one researcher has solved the Hamiltonian path problem: is there a path which passes through every vertex exactly once, including entering on one vertex and exiting on one other? For the seven vertices in Fig. 11, the path solving the problem is shown for the case where one enters on vertex 0 and leaves from vertex 6. There exist algorithms for finding the solution to this question, but a solution is often computationally intractable with current computing resources. A brute force

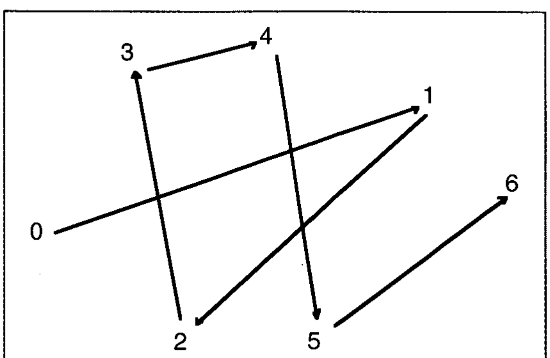

Fig. 11. Hamiltonian path through directed graph (after [59]).

method to find the desired path is to generate many random paths through the graph, then successively filter out paths that do not meet certain criteria. Any remaining path is the Hamiltonian path. Drawing on biological techniques, Adleman [59] represented the vertices of a directed graph as nucleotide chains. He also represented paths among the vertices as nucleotide chains. The solution was implemented by combining and purifying these nucleotide chains. The final nucleotide chain gives the answer. The promise of this method is the capability of performing many computations simultaneously, in parallel. Also, as Adleman explains, the use of energy is highly efficient.

The computational applications of biology have in one sense already been demonstrated [60]. A science fiction pundit would look at the biosphere as the ongoing computational result of DNA-based computation, set into motion millennia ago by some as yet unknown force. In other words, consider an individual protein, an individual biological structure, or an individual from any species as the current output of a long string of ongoing evolutionary computation. Our ability to tap this computational power is intriguing, and obviously still in its infancy.

3 LESSONS FROM A HISTORICAL RETROSPECTIVE

From our current vantage point, how can we know the future of technology? Of course we cannot. But spending a few moments on historical developments in technology can shed light on the magnitude of changes that we can expect.

3.1 Hearing Partials

To revisit the introduction, the history of audio engineering is shaped by the history of technology enabling people to transmit, record, analyze, and reproduce sound, often musical sound. What then are the characteristics of sound that must be captured by technology? Sound is propagated as a disturbance in a medium, traveling at a certain speed. A recording of the disturbance in the medium has a certain shape. If the disturbance is more or less periodic, there is a fundamental frequency. In most real-world sounds, not all of the constituents are exact harmonics. Sound comes from a direction and distance that can usually be judged by a human listener. The sound source can be identified. And so on.

How recently did we learn such things? Consider something as simple as the speed of sound in air. This was not determined experimentally until just a few hundred years ago [61]. What about the breakdown of sound into a fundamental and harmonics? It is so intriguing to read Mersenne's account from 1636 of his ability to analyze sounds with his own ear: "a struck or sounded string, when open, makes at least five different tones at the same time, of which the first is the...fundamental [fondement]. ...it is necessary to find complete silence to perceive them. ...Musicians...must have patience, or they must take a bass viol, on which they play the sixth, fifth, or fourth string at night and be extremely attentive...these sounds follow the ratio of these numbers, 1, 2, 3, 4, 5, since one hears four different natural tones, the first of which is at the upper octave, the second at the twelfth, the third at the fifteenth, and the fourth at the major seventeenth" [62]. We might scoff that Mersenne was only claiming to listen for something that he already knew was there. But he couldn't have known, since the mathematical relationship between a waveshape and its constituents was not codified until about two centuries later, not to mention the capability of recording the waveform.

3.2 Seeing Atoms

There is an interesting parallel in the state of the art of our understanding of matter. Just as a few hundred years ago researchers had no way to record a waveform or analyze it mathematically, so now, our means of knowing the position and characteristics of individual atoms remain very primitive. If you cannot see the edges and corners of an atom or molecule, how can you know how to grab onto it when you want to move it? Regis [39] has an interesting account of the work of Erwin Müller [63, 64] who developed the field emission microscope, one of the first methods for observing the inner structure of molecules. In this microscope, a needle is embedded in a vacuum tube. A high electrical current applied to the needle causes electrons from the needle to be cast onto a fluorescent screen. The pattern on the screen in turn gives some information about the structure of the tip of the needle. To increase resolving power, Müller turned to using protons, which however produce a fainter image on the screen. "The best way to observe the screen is directly with our eyes, after they have been conditioned by a long period of darkness" [63, p. 62].

Here we have Mersenne, a few hundred years ago, listening with his own ears at night when it is quiet, coming up with the first analyses of musical sound. Now we have sophisticated tools to record and analyze musical waveforms. A few decades ago, an eminent scientist is likewise starting off on an analysis of matter, sitting in darkness until his eyes can adjust. It is awe inspiring to imagine how to use the advances made in audio since Mersenne's time to extrapolate into the future from the work of Müller and others in our time. We can only be sure that the technological advances will be striking. The same is true for other technologies considered here.

4 CONCLUSION

One does not have to be a devout Buddhist to appreciate the Buddhist maxim that "everything changes." Given the amount of fundamental change in the history of our industry, and given the large forces behind newly developed technologies, it is to be expected that new technologies will effect massive change on our industry.

In my opinion, as digital electronic technology took hold in our industry, we adopted a rather passive attitude. This has had ramifications in everyday engineering. Let me give one example. In my own software consulting practice, I have repeatedly encountered a hardware design for a "multimedia" device in which perhaps 90% of the available resources are already dedicated to processing visual information. The designer (who often has a background in digital graphics) has reasoned that the data processing rates are so high for visual information that this must be so. At the end of the design process, an audio consultant is to be brought in "to make audio work" with the remaining 10%. But the audio domain differs from the visual in one important respect. When a moving visual image is interrupted, there is no physical medium that keeps moving. But in the audio world, some physical device is already in motion as the result of an audio data stream. We all know that interrupting an audio data stream in the digital domain results in clicks and pops, but the rest of the computer industry often misses this. The proverbial 10% of the resources allocated to audio may not suffice to guarantee real-time audio throughput.

This is one example. The point is that as digital technology swept across society, the audio industry did not steer how the technology would be adopted. Instead, it waited until the technology was stable, then adopted the technology as best it could. In the face of technologies which will be coming our way, we have a choice as an industry and as a Society. Do we wait until the technology is developed, then adopt it for our own use? Or do we work proactively to guide the development of the technology?

The founders of our Society have done a superb job bringing us to the admirable place where we are today. The Society is active in standards work, conventions, local chapters, technical conferences, the *Journal*, other publications, education, and many other areas. Our Society has reached a position of strength and stability. We have also gathered several decades' experience in adapting to new technologies as best we can. Given that we can foresee technological change coming from without, I think that it is now time for our Society to take a proactive role in guiding the development of new technologies to best serve our interests.

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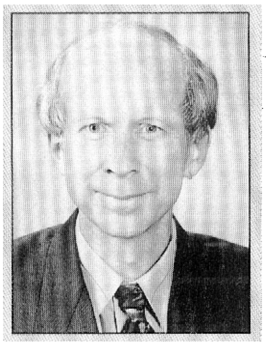

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