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SONIC EUKARYOTES: SONOCYTOLOGY, CYTOPLASMIC MILIEU AND THE TEMPS INTERIEUR

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> At the beginning, the whole body or organism raises up a sculpture or statue of tense skin, vibrating amid voluminous sound, open-closed like a box (or drum), capturing that by which it is captured. We hear by means of the skin and the feet. We hear with the cranial box, the abdomen and the thorax. We hear by means of the muscles, nerves, and tendons. Our body-box, stretched with strings, veils itself within a global tympanum. We live amid sounds and cries, amid waves rather than spaces the organism moulds and indents itself…I am a house of sound, hearing and voice at once, black box and sounding-board, hammer and anvil, a grotto of echoes, a musicassette, the ear's pavilion, a question mark, wandering in the space of messages filled or stripped of sense.…I am the resonance and the tone, I am altogether the mingling of the tone and its resonance.[i]
>
> –Michel Serres

> That we have no ears to hear the music the spores shot off from basidia make obliges us to busy ourselves microphonically.[ii]
>
> –John Cage

INTRODUCTION

Saccharomyces cerevisiae, more commonly known as yeast, is a unicellular fungus with a cell cycle similar to that of humans. The first eukaryote to have its genome fully sequenced and a standard model organism in biology research,[iii] yeast is an organism that lends itself easily to multisensory experiences. It has been imaged extensively with light and atomic force microscopy, and anyone who has seen the bottom of a pint glass or walked past a bakery can speak to *S. cerevisiae's* olfactory and gustatory allures. It is fitting, then, that this species is also the first to have its cellular noises amplified and recorded.

Sonocytology, a recently developed technique within nanotechnology research, uses a scanning probe microscope to record the vibrational movements of cell walls and amplifies those vibrations so that humans can hear them. Yeast cells vibrate approximately one thousand times per second, and most cells vibrate within the frequency—though not amplitude—range of human hearing. Humans can hear as sound any vibration that has a periodicity in the range of twenty to twenty thousand vibrations per second (Hertz). The vibrations of cells are well within the frequency range of human hearing—in musical terms, from the C-sharp just above middle C to the following D, a half-step up—but the amplitudes of their vibrations are too low to be within normal hearing range (the cell wall is displaced only three nanometers each time it vibrates) (Wheeler 2004). By amplifying the vibrations of cells, researchers essentially 'turn up the volume' on cellular vibrations. In this paper, I will address how raw cellular vibrations are converted into cellular sounds that scientists can interpret as conveying meaningful information regarding the dynamism of cellular interiors. Further, I will examine the conditions that enable scientists to describe cells as actors capable of 'speaking' or 'screaming,' and how listening to cellular sounds may eventually change how scientists think about cells—as subjects that are dynamic, environmentally situated, and experiential.

Jim Gimzewski, a scientist in the Department of Chemistry and Biochemistry at the University of California, Los Angeles, is best known for the nanotechnology research he conducted while at the IBM Zurich Research Laboratory, where he built the highly publicized molecular abacus and molecular wheel (Cuberes et al. 1996, Gimzewski et al. 1998). A celebrity in the nanotech world, he has received numerous honors and prizes, including the prestigious Feynman prize for nanotechnology research.

With his graduate student Andrew Pelling, in 2004 Gimzewski used an atomic force microscope (AFM) to record the nanomechanical motion of yeast cells. Atomic force microscopy has been used to probe the surface of *E. coli*, to image biomolecular reactions as they occur, to measure the molecular movement of cardiomyocytes (heart muscle cells that contract rhythmically in culture), and to track the movements of flagella and cilia. Gimzewski's original intention was to record the movement of cardiomyocytes, which were sent to him by Carlo Ventura, a Sardinian medical researcher Gimzewski had met at a conference in 2001. Gimzewski's stem cells were scheduled to arrive from Sardinia on September 11, 2001. In the heightened state of national security immediately following 9/11, Gimzewski's stem cells were deemed a potential threat and were seized by customs (Wertheim 2003). Frustrated and impatient to begin his work with the AFM, Gimzewski borrowed a yeast culture from colleagues in a nearby lab and was surprised to discover that yeast vibrate with a regular periodicity.

The atomic force microscope was manufactured in the 1980s and is now indispensable to nanotechnology work. While light microscopes cannot resolve objects smaller than half the length of a light wave, the atomic force microscope resolves this problem, which scientists term the Rayleigh limit, by using a nanometer-size probe to map the topology of the object being imaged. As a tiny cantilever (its tip is less than ten nanometers wide) is displaced by the surface of an object, a piezoelectric crystal converts nanomechanical motion into voltage, creating a map of the surface. However, instead of dragging a probe over the surface of a sample, Gimzewski held the AFM probe stationary on the surface of a yeast cell so that the oscillations of its cell wall could be traced. Yeast cells, about five microns in length, have cell walls much more rigid than most mammalian cells, a characteristic that makes it easier to rest a microscopic probe on their surface in order to detect cellular vibrations. Gimzewski discovered that yeast cells vibrated rhythmically, and that the periodicity of the vibration was within the range of human hearing (the wave fluctuated between 20 and 20,000 times a second). Using a computer program available on the Internet, he converted the vibrations recorded by the AFM into an electronic sound file. Gimzewski believes that sonocytology is preferable to other techniques for rendering cellular interiors because it is non-invasive, using no dyes, fluorescent markers, or quantum dots (Pelling et al. 2004). He argues that the synchronized movement of motor proteins 'cannot be observed by traditional cytological methods and occurs in cells in their natural state.' The movements of these molecular molecules are, Gimzewski says, 'too small and fast to be seen on video' (Pelling et al. 2004: 1150).

How do acoustic technologies change what it means for something to be audible, given that sound is by definition a vibration that can be heard by some organism? Jonathan Sterne defines sound as 'a product of the human senses and not a thing in the world apart from humans' (Sterne 2003: 11). Extending Sterne's definition, I include under the rubric of 'sound' vibrations perceptible to any organism: that is, sound is the sum total of Serres' 'global tympanum'—a soundscape filled with 'waves rather than spaces' that 'moulds and indents' listening organisms. A vibration is not necessarily audible, and sounds are not inherently meaningful. Only mechanical oscillations within a small range of frequency and amplitude are audible without technical manipulation. *Sound* is any vibration that is within the range of an organism's hearing, or, since the advent of acoustic technologies, of an organism-acoustic machine assemblage. Because sound by necessity is related to a biological sensorium and assumes a 'tuned in' body, it has a semiotic component, one that is parsed in historically and socially specific contexts. If a signal is not deemed meaningful by a listening body, then it is *noise*—'irrelevant or superfluous information' (OED) that can interfere with the transmission of information. A *signal* is a sound that a listener regards 'as conveying information about the source from which it comes' (OED).

Cyrus Mody, in his ethnographic account of how sound structures laboratory experimentation and contributes to the construction of scientific knowledge, argues that the separation of good sound out of acoustic contamination is a contingent, context-specific, and evolving process.[iv] Apart from vibrations, which refer to a purely physical phenomenon, *sound*, *noise*, *signal*, *music*, *voice*, and *scream* each assume a listener who can make judgments as to the ontologies of an acoustic resonance and its source. A listener designates a sound as *music* if he or she judges that someone composed it to be rhythmic, aesthetically pleasing, or otherwise expressive. To claim that a sound is a *voice* is to imbue the sound's source with the agency to utter sounds that convey information. A *scream* is inarticulate speech made by a human to express extreme pleasure or pain. Non-human animals are rarely described as 'screaming': instead, they screech, squeal, yelp, or howl. Attending to how cellular oscillations are alternately described as sound, noise, signals, music, singing, or speaking reveals something about the way listeners interpret cellular agency and subjectivity.

Much in science studies has been written on the role of visualization in scientific research. Indeed, visual concerns as well as metaphors are central to STS theories: science studies scholars speak of inscription devices (Latour and Woolgar 1986), traces (Derrida 1967, 1993), drawing things together (Latour 1990) and *Drawing Theories Apart* (Kaiser 2005), the god's eye view from nowhere (Haraway 1988), *homo depictor* (Hacking 1983) and unconscious optics (Benjamin 1936).[v] From Foucault, scholars learned to think about pan*optic*ism and the anatomy of power; feminist and psychoanalytic theory spoke of the gaze, and postcolonial studies exported the I/eye.

In contrast, with the exception of recent analyses of the scientific uses of space sounds (Johnson and Lecusay 2005), underwater sounds (Helmreich 2005), and laboratory sounds (Mody 2005), acoustic technology in scientific research has been understudied and undertheorized by STS scholars. Trevor Pinch and Karin Bijsterveld's special issue of *Social Studies of Science* does not examine sound as scientific data, though the editors do open up a critical dialogue between science studies and sound studies, emphasizing that science studies can offer 'a focus on the materiality of sound, its embeddedness not only in history, society, and culture, but also in science and technology and its machines and ways of knowing and interacting' (Pinch and Bijsterveld 2004: 636). In his study of contaminating noises in laboratory science, Cyrus Mody shows that researchers diagnose problems in their microscopes by listening to them and that this auditory transmission of tacit knowledge imparts a 'more embodied interaction with the instrument' (2005: 188). He calls for a more anthropologically motivated thick description of the place of all the senses in laboratory practice. While Mody examines how acoustic contamination dictates the structure of experimentation in materials science laboratories, I will attend to the status of sound as primary scientific data—that is, I will be focusing on sound as scientific signal, rather than noise. Understanding that separating out meaningful data from experimental contamination is always a culturally determined judgment, I will examine how scientists make sense of cellular noises. Parsing cellular signals from noise, I argue, is determined by scientists' understanding of cells as subjects capable of speaking to their conditions.

What sorts of new soundscapes (a term coined my R. Murray Schafer in 1968 to emphasize the ecology of sound) are created by acoustic technologies, and how are they listened to, explored, and made sense of by scientists through the mediation of technology? This paper will analyze how sonification constitutes scientific objects and how scientists use sound to represent these scientific objects as subjects. While subjectivity implies the ability to speak to one's conditions, it also suggests that actors' utterances are conditioned by epistemic and ideological regimes, and I will point to the ambiguity between cells speaking and cells being spoken *for* that is produced by the technique of sonocytology. I will attend to how ra*w sound* is transformed into *signal*—that is, how scientists convert inchoate cellular vibrations into meaningful scientific data. Further, I will examine how sound could reconstitute scientific and lay understandings of cellular interiors. In order to answer my animating question, how sound might change how scientists perceive and understand cellular activity, I will first describe how sonocytology developed and how scientists and popular press have turned to metaphor in order to make sense of cellular noise. I will then focus on three epistemological effects of using sound scientifically to explore otherwise inaccessible spaces: the first concerns the ways we think about organisms in their environment and in relation to other organisms, the second bears on the question of how we think about the insides of organisms as stages on which dynamic biological processes are performed, and the third asks how listening affects—and also effects—our own tactile and embodied contact with these entities. I will track back and forth between these matters of space, time, and embodiment in my analysis, because the three are intimately related through sound.

In my explication of how sound affects the way we might yet understand cellular interiors, I employ Canguilhem's concept of *milieu*—an array of decentered and mutually influential relations between an organism and its surrounding environment—to argue that sound clues us into the material situatedness of cellular life. Sound, by inviting listeners into the environment of the sound's source, creates a soundscape in which the different milieus of people and cells can resonate. I will draw upon the diverse meanings of *transduction* —broadly, the conversion of a signal from one medium to another—to think about how sound travels through different material environments and how it is converted into scientific information.

Second, I assert that sound makes it possible to access *in situ* the biological processes that occur on the interiors of bodies and cells, to understand bodies and cells *in time* and *in context*. While STS scholars have critiqued science for reducing subjects to experimental objects, I will examine how scientists are making sense of cellular noises and how sonification constructs a particular form of technically and socially mediated cellular subjectivity.

Sound has been used in science to explore and gain direct experience of inaccessible places: to sound out the depths of the ocean, the inside of the body, and the furthest reaches of outer space (where the further away the sounds originate, the older they are—physicists recently analyzed sound waves originating in the early universe to extrapolate the age and structure of the universe) (Bennett et al. 2003). Acoustic technology is also used to connect with absent loved ones, as when telephone wires and satellites transmit disembodied voices, or with people on the margins of life, as in the use of early sound recording to embalm the voices of the dying and the more recent use of ultrasound in obstetrics (Kittler 1986, Ronell 1989). Sound in each of these cases offers access to an imagined space and time—on the outskirts of the universe, inside a beating heart, at the bottom of the sea, long ago or very soon.

LISTENING TO CELLS

When Gimzewski examined the data recorded by the atomic force microscope and realized that yeast vibrate regularly, he went online and downloaded a computer program that could convert the vertical deflection data into a wav file (Pelling and Gimzewski originally used a program called Awave, later switching to SpectrumPRO).[vi] When he ran Awave on the lab computer and turned on the speakers, an ethereal noise filled the laboratory.[vii] Beginning to experiment with the noise produced by yeast, he recorded the vibrations they made at different temperatures and in different solutions. When he added sodium azide, a chemical that shuts down cellular metabolism, to the yeast, the resulting noise sounded like radio static. Gimzewski believes this sound is an indexical representation of the Brownian motion of molecules, since sodium azide stops all ATP-driven nanomechanical activity. When he doused the yeast in alcohol, the pitch of their vibration increased. In an interview, he described the resulting sound: 'It screams. It doesn't like it. Of course, yeast produces alcohol as in beer production, but if you put strong alcohol like Absolut vodka on it if you like, then it screams. It screams. It doesn't like it' (Kestenbaum 2004). He speculates that 'screaming' is the sound of molecular pumps working overtime to expel the alcohol.

Gimzewski endows the yeast with agency when he says that when doused with alcohol they 'scream' because they 'don't like it' (Kestenbaum 2004). Characterizing the sounds made by yeast as 'screaming' seems like an odd descriptive choice, as it suggests that Gimzewski's experimental interventions cause the yeast pain. Popular science articles about sonocytology picked up this metaphor, describing Gimzewski as the 'master of this cellular torture chamber' (Zandonella 2003: 106). The suffering of model organisms, which makes most scientists uncomfortable, is usually expunged from professional and popular accounts of scientific research (Lynch 1988). Screaming is not just any kind of signal, it is an inter-relational, emotionally loaded message uttered either in pleasure or pain: 'screams demand urgent or empathetic responses and thereby create a concentrated social space bounded by their audibility' (Kahn 1999: 345). Screaming, a mode of communication usually only attributed to humans, is here more than a response to environmental crisis. Interpreting cellular noise as 'screams' forces an attention to the shared cellularity of humans and yeast, and to the fact that yeast are model organisms that stand in for humans in biomedical experiments. In so doing, scientists transform objects of scientific research into agential cellular subjects by calling upon an anthropocentric model of subjectivity.

Describing the sounds made by yeast provokes flights of fancy and metaphor as scientists and journalists alike struggle to find words that describe something new in familiar terms: articles on Gimzewski's technique have likened the sound to the whistling of singing whales (Lurie 2004), and compared the AFM to a microphone (Jaffe 2004: 50), a new musical instrument (Niemetz, in interview), or, as Pelling suggests, a record needle (Wheeler 2004).[viii] Gimzewski tells reporters that if yeast were the size of humans, their sounds would be closer to the volume of 'ordinary conversation' than of loud music, and that 'If you were to shrink down to the cell's size, it would be like holding a transistor radio to your ear' (Jaffe 2004). When Gimzewski and Pelling published their findings in *Science*, representatives of the Maharishi Mahesh Yogi approached them, thinking that they'd 'discovered "the language of life"' (Thompson 2004).[ix]

While the sounds produced are conversions of the vibrations of the surfaces of yeast cells, Gimzewski believes the sound provides access to the workings of the cellular interior by indexically[x] signifying cellular metabolism and movement. Describing the technique he developed, Gimzewski says: 'We gently touch a cell, a living cell and we listen….

They actually produce a kind of music and you can hear it' (Lurie 2004). He says the music made by the cell is 'amazing' (Kestenbaum 2004) and 'beautiful' (Thompson 2004). Gimzewski's characterization of cellular vibrations as music is predicated upon a definition of sound as something audible not only to the ear, but to the ear with the aid of technical amplification. Like John Cage's basidia spores, the yeast are already making music; we just have to 'busy ourselves microphonically' in order to hear it. Calling these sounds *music* also casts the organism as composer, extending authorship and artfulness into the natural world.

Gimzewski compares listening to the vibrations of yeast to standing outside of a factory and hearing the hum and beat of machines operating inside the factory walls, pointing out that during the Industrial Revolution trained mechanics could diagnose what was wrong with a machine just by listening to it (Kestenbaum 2004). Extending and concretizing this analogy between cells and machines, Gimzewski is now attempting to apply sonocytology to clinical diagnostics, listening for the difference between healthy and cancerous cells.

Gimzewski believes that sonocytology has potential diagnostic applications because cancerous cells metabolize ATP more quickly and therefore vibrate at a higher frequency than non-cancerous cells. He hopes that eventually clinicians will be able to detect cancer at an early stage by listening to cells. However, one obstacle to a medical application of sonocytology is the fact that mammalian cell membranes are much less rigid than yeast cell walls. Nonetheless, Gimzewski has begun collaborating with Michael Teitell, an immunologist who develops animal models for lymphomas (Wertheim 2003). Teitell exposes human and mouse osteocytes to chemical mutagens and Gimzewski tries to identify which cells are cancerous using sonocytology. Cellular sounds are not necessarily meaningful to cells themselves, but instead could be made meaningful through human audition.

Other scientists have suggested that the vibrations picked up by the AFM are signals cells use to communicate with one another. Kerry Bloom, a mycologist at the University of North Carolina, points out that it was a 'big surprise when people played rock music to plants, and there was a chemical reaction inside the plants when you played the Stones at high volume. And so now I would argue the same thing is true with anything with a cell wall. The same output could be another level of signaling' (Kestenbaum 2004). Inscription devices turn occurrences into events, and the AFM turns sonic and informatic noise into a meaningful message.[xi] In attempting to make sense of cellular noise, Bloom speaks on the yeast's behalf.

ACOUSTIC MILIEUS

Historian of technology Emily Thompson defines a soundscape as 'simultaneously a physical environment and a way of perceiving that environment; it is both a world and a culture constructed to make sense of that world' (2002: 1). Bound up in the process of turning sound into data is the listeners' culture, the environment in which the sound reverberates, and 'the material objects' within that environment 'that create, and sometimes destroy, those sounds' (ibid). That is, soundscapes are both acoustically and culturally immersive.[xii] How does sound condition an organism's environment, and how does that environment affect what kinds of sound count as signals and which are merely noise? I will filter Canguilhem's notion of the *milieu* through theories of soundscapes to analyze how listening to cellular noises clues scientists in to the way each cell is embedded in, and in a mutual relation to, its own microenvironment. Symmetrically, just as cellular noises draw attention to cells' immersion in extracellular environments (in this case, the constructed environment of the laboratory), the interpretation of cellular noises is embedded in the listener's culture. Tying cellular and cultural immersions together, I will later think about how listening to cells creates a space in which cellular and human milieus resonate.

Gimzewski's atomic force microscope is housed in a special darkened noise-free room, kept inside a thermally, acoustically, and electrically isolated chamber lined with foil on a vibration-free platform suspended in air. The care taken in isolating the AFM from any vibration is necessary in order to verify that any vibrations recorded are due to cellular activity and not to any external noise (here I mean *noise* both as external phenomena, in the sense of sound, and figuratively, as a disturbance in a signal). The vibration of the AFM probe due to random external vibrations is less than the length of a single atom. Ironically, in order to listen to the vibrations of cells 'in their natural state' (Pelling et al. 2004: 1150), a very artificial environment must first be constructed for them.

Not as much a place as a relation between an organism or some other biological system and its ambient environment, the milieu is a landscape that influences and in turn is shaped by the organism that occupies it. The notion of milieu fastens organisms to the web of particularities of their environment, drawing attention to an organism's interaction with its environment and with the other organisms in it. In his explication of the conceptual evolution of *milieu*, Canguilhem writes, 'This explains the passage from the notion of fluid as a vehicle to its designation as a medium [*milieu*]. The fluid is the intermediary between two bodies; it is their milieu; and to the extent that it penetrates these bodies, they are situated within it' (Canguilhem 1952: 8).

He continues:

> In the success of the term 'milieu,' the metaphor of the line or the indefinitely extendable plane, being both continuous and homogeneous, with no definite shape or privileged position, wins out over the metaphor of the sphere or circle, shapes that are still defined qualitatively and, we might even say, attached to a fixed central reference point. Circumstances and surroundings still retain a symbolic value, but milieu abandons any evocation other than a position indefinitely denied by exteriority. The now refers to the future, the here refers to its beyond, and so forth always ad infinitum. The milieu is really a pure system of relationships without supports (ibid: 11).

Thinking through the milieu in terms of soundscapes, sound can draw attention to the material medium in which an organism is situated: sound vibrations travel through air or water and refract off other objects inhabiting the milieu. It is important to note that all of the yeast sounds Gimzewski recorded were differentiated by the type of environment in which the yeast cell was situated: its temperature, osmolarity, the presence or absence of sodium azide or ethanol. The resulting sounds, indexical of cellular responses to extracellular circumstances, demonstrate the porosity of the cell wall, blurring the boundary between intracellular and extracellular landscapes.

So too, the experience of listening reconstitutes the listener's body's relation to its own environment. Julian Henriques describes the experience of listening to dub music: 'You feel the pressure of the weight of the air like diving deep underwater…. making the experience imminent, immediate, and unmediated' (Henriques 2003: 452). Sound is also a system of relations between at least two bodies. It requires an origin as well as a receiver to sense audible vibrations. While sound has a point of origin, there is no center to the space through which it is transmitted. Bodies are both situated within an acoustic space and are 'penetrated by it:' it 'is a kind of space you are inside as well as outside and it is inside you as well as you being inside it' (ibid: 459). Now compare Canguilhem's biological milieu to McLuhan's coinage of auditory space:

> It is the act of hearing that itself creates 'auditory space,' because we hear from every direction at once. …Auditory space, so crucial to architectural problems today, is usually defined as '*a field of simultaneous relations without center or periphery*.' That is, auditory space contains nothing and is contained in nothing. It is quite unvisualizable, and, therefore, to the merely print-oriented man [sic], it is 'unintelligible' (McLuhan 2005: 49, emphasis added).

Auditory space implies a listener who defines and demarcates it. That is, auditory space must by definition be a *biological* space, one inhabited by organisms busy making noises and listening to their own and others' sounds. It is a perceptual field but it is not immaterial or purely informatic: sounds require topographies, media of transmission, listening bodies.

A series of milieus is folded into the practice of sonocytology. Each milieu is an array of relations that also links to other milieus. There are the milieus of the scientist, who might be ensconced in a sound and vibration-free room (manipulating the probe of an atomic force microscope, for example), sitting in front of a computer listening to yeast sounds as they flood from the speakers into the lab, or designing artistic environments to evoke cellular processes for lay audiences. There is also the milieu of the yeast cell; because the cell cannot be taken out of fluid without dying, it is suspended in a fluid 'yeast extract' medium and flushed through a lattice of 5 μm pores so that one yeast cell is trapped in each pore before being placed in a Petri dish and doused in yet another medium made of pulverized potatoes. Corralled in a polycarbonate pore and pinned by the tip of the AFM probe, the yeast vibrates in its isolated chamber. Beneath the cell wall of the yeast lies a cytoplasmic milieu inhabited by organelles suspended in cytoplasm and motor proteins that transduce chemical energy from ATP into motor energy, with which they build cellular scaffolding and traffic molecules through the cell. The transduction of sound from each of these milieus to the next constructs a soundscape in which cellular processes become sensible to biologists, once they have learned to interpret what they are hearing. Resonances scale the domains and temporalities of previously isolated milieus. For Deleuze and Guattari,

> Every milieu is coded…but each code is in a perpetual state of transcoding or transduction. Transcoding or transduction is the manner in which one milieu serves as the basis for another, or conversely is established atop another milieu, dissipates in it or is constituted in it…. the milieus pass into one another; they are essentially communicating (1987: 313).

An acoustic milieu, then, is a milieu shared by two (or more) organisms that are in some kind of relation to each other and to their surroundings. If 'the milieu that is proper to man [sic] is the world of his perception' (Canguilhem 1952: 26), then listening to yeast creates a shared milieu occupied by yeast and their audience. It is into this thumping cytoplasmic milieu that we imagine ourselves when listening to cellular noise.

But listening happens in time and cellular activity is dynamic, so we must also attend to the modes in which sound is transmitted through acoustic milieus. As sound travels through media and mediating machines, it is transduced. Transduction, as engineers use the term, refers to the technically mediated process by which mechanical vibrations are converted into electrical signals. Emily Thompson argues that the technical and material development of transducers in the 1920s and 1930s significantly affected the epistemology of sound: 'the scientists who used these tools [electroacoustic transducers] began to effect similar transformations between sounds and signals in their minds, developing new ideas about the behavior of sound and the physical objects that produced it' (2002: 96). That is, by turning sound into an electrical signal that could be amplified, manipulated, and transformed, acoustic technology turned sound into information that could be fruitfully studied by scientists and used as data with which to gather information about natural phenomena.

Transduction has three definitions, all of which apply to sonocytology:

1. Acoustic—the conversion of a signal, such as a sound wave, from one medium to another.
2. Biological—the transfer of biological information from one organism to another; or the translation of a stimulus into an electrical impulse.[xiii], [xiv]
3. Technical—the conversion of input energy into output energy of a different form by a transducer such as a piezoelectric crystal (of an atomic force microscope) or a microphone.[xv]

Piezoelectricity means the reversible conversion of mechanical energy into electricity; microphones transduce mechanical vibrations into electrical signals, and speakers do the reverse. In addition to microphones and speakers, a third kind of transducer is at work here too—the human sensorium is understood to convert mechanical energy, light, and chemical stimuli into electrical impulses:

> Hearing is understood…in terms of a work of transformation. Hearing takes what Serres calls the hard, *le dur*, and converts it into information, *le doux*, or the soft [Serres 1998: 141-9]. This exchange is effected by the senses, or by the works of sensation, which, in turning raw stimulus into sensory information, also make sense of the senses, effecting a slight declination, or deflection within the word *sens* itself: sense becomes sense. These transformations are effected in every organism by a series of processes of transformation that Serres is wont to call 'black boxes' (Connor 2005: 323-324).

The yeast/atomic force microscope/human assemblage that performs sonocytology is a series of vibrations traveling through different material media and converted by mediating transducers into sound.[xvi] The kinetic motion of motor proteins becomes a cytoplasmic rumble that vibrates the cell wall, which exerts pressure on a cantilever, causing the piezoelectric crystal to convert the deflection into an electrical output, creating a graphic trace of its deflection, which is then converted using a computer program into an electrical signal pumped out of a pair of speakers as mechanical wave oscillation, creating a periodic turbulence in the air that vibrates the tympanum, that vibrates the ossicles, that vibrates the fluid of the cochlea, that triggers hair cells to send electrical signals to nerves that travel to the brain, in which each time the signal travels from one neuron to another it must be transduced from electrical to chemical energy while traveling through the intercellular synapse. The acoustic, the technological, and the biological harmonize with one another in a biological soundscape. However, the biological soundscape is in turn culturally transduced so that the technical conditions of its production are obscured.

TEMPS INTERIEUR

Sound triangulates between space and time, drawing listeners' attention to the physical medium through which it is transmitted. It places objects in space and floods space with time.

Space indexes the distribution of sounds and time indexes the motion of sounds.

Yet acoustic time is always spatialized; sounds are sensed as connecting points up and down, in and out, echo and reverb, point-source and diffuse. And acoustic space is likewise temporalized; sounds are heard moving, locating, placing points in time. The placing of auditory time is the sonic envelope created from the layered attack, sustain, decay, and resonance of sounds. The placing of auditory space is the dispersion of sonic height, depth, and directionality (Feld 2005: 185).

Sonocytology captures the vibrations caused by intracellular processes unfolding in the cytoplasmic milieu. Pressing our ears to opaque cell walls, we hear the inner cellular activity unfold in four dimensions: the busy hum of actin and myosin filaments assembling cellular scaffolding, the whoosh of molecular transport through cytosol, the glub glub of endocytosis and exocytosis. In this section, I interrogate how sound indexically represents dynamic interior biological processes, and how temporality is related to the way biologists conceptualize the insides of cells. Drawing upon Canguilhem's *milieu intèrieur*, which refers to interior space, I have coined *temps intèrieur* to express the interior time of an organism.

Sonocytology has been met in the scientific world with reserve and occasional skepticism: some scientists are unsure whether the sound recorded by the atomic force microscope originates within the cells. They have raised the possibility that the vibrations could be due to external factors, such as Brownian motion or the unintentional movement of the AFM probe. However, Gimzewski and Pelling are certain that what they are hearing is the sound of cellular metabolism and the movement of motor proteins, positing that their 'experiments reveal a new aspect of yeast cell biology—the *dynamic nanomechanical activity* of the cell wall' (Pelling et al. 2004: 1150, emphasis added). The fact that the frequency of the cellular sounds is dependent on the temperature and metabolism of the yeast strongly supports their claim.

Gimzewski compares the atomic force microscope reading the topology of a microscopic surface to a blind person running his finger over a line of Braille (Gimzewski and Vesna 2003). But instead of running the tip of the probe over a surface, Gimzewski holds the probe in place over a yeast cell and measures the displacement of the cell wall, a technique he compares to 'using your finger to feel a pulse' (Kestenbaum 2004). The comparison of cellular movement to a beating heart is not accidental: the beating heart stands as an icon of life and motion (Kuriyama 2002). Mediate auscultation, tissue culture, cinematography, and atomic force microscopy have each listened to, isolated, visualized, or probed hearts in an attempt to get closer to the locus of organismic vitality.

One of the first tissues to be kept alive outside of an animal body was a culture of chicken heart cells. Heart cells were chosen 'from all possible organs and tissues of the body to demonstrate permanent life and rejuvenation by culture with a tissue that would manifest life most obviously: the beating heart' (Landecker, forthcoming). Heart cells that continued to beat in culture constituted the most publicly convincing demonstration of artificially sustained life in part because both scientists and laypeople could associate beating hearts with the lively rhythm of their own bodies:

> The combination of this natural animate function that every reader could feel thumping away within themselves and the familiar, everyday inanimate object of the glass jar…resulted in the distinctly uncanny image of life continuing severed from the body and contained in glass (ibid).

Scientists marveled as heart cells continued to beat autonomously outside of the animal, as if the rhythmic movement of the cells made them more noticeably alive than living, yet stationary, cells. Half a century earlier, Etienne-Jules Marey, a physiologist who invented techniques for representing physiological mechanics and animal locomotion, developed instruments like the cardiograph and the sphygmograph to measure the pulse. In one experiment, he inserted air-filled ampules into a horse's beating heart and recorded its contractions using a kymograph (Cartwright 1995: 24). In one of the first uses of the cinematograph to study animal physiology, Ludwig Braun filmed the contractions of a dog's heart in 1898 (Cartwright 1995: 20).

The heart is also central to the application of atomic force microscopy to biological research: the mechanical pulse of embryonic chicken cardiomyocytes in culture is a primary object of analysis using AFM in biophysics (Domke et al. 1999), as is the movement of cilia and flagella. But prior to Gimzewski's idea to convert AFM data to sound, the pulsing and vibrating of cells had only been measured graphically. Gimzewski first thought of sonocytology in 2001, when he learned from Sardinian colleague Carlo Ventura that cardiomyocytes grown in culture contract and relax rhythmically in a Petri dish. He wondered whether other cells also pulsated and if so, whether those fluctuations could be within the range of human hearing. As in earlier experiments with measuring the heartbeat, the animation of heart stem cells in Gimzewski's lab also is easily mistaken for life. Science journalist Margaret Wertheim, upon seeing Gimzewski's heart cells in culture, exclaimed:

> Though there is no body here, no actual organ, rhythmic waves course through the cell community. It's an eerie sight, as if the culture were straining toward organismic identity. This phenomenon has inspired Right-to-Lifers to declare that an 18-day-old fetus has a heart and is, hence, a fully charged human: I beat, therefore I am (Wertheim 2003).

Hannah Landecker, in her history of *in vitro* life, elucidates the connection between understandings of the interior and exterior of an organism and notions of time. Before tissue culture, scientists who wanted to represent different stages in some biological process over time had to kill organisms or tissues at each successive stage of the process being studied in order to create a composite image of, for example, cell growth and division. By taking tissue out of the interior milieu of the organism and placing it in an external, artificial milieu, scientists were able for the first time to watch interior biological activity unfold under glass: 'Internal processes could be placed on the exterior, and watched…. Something opaque was replaced by something transparent, and the enclosure did not have to be opened or halted in order to observe what was going on inside it' (Landecker 2002: 690).

The 'vibrating world,' in which sound is only a small, biologically mediated, fraction of all physical vibrations (Sterne 2003: 11), likewise reveals interior processes, making the *temps intèrieur* accessible, immediate, and mediated outside of the cell. While scientists cannot examine cellular activity outside of the cytoplasmic milieu, the cellular interior can be sonically projected into an external acoustic space, rendering the dynamism of intracellular processes sensible and present. Sonocytology, like tissue culture, turns the body inside out in order to render the dynamic interior processes accessible.

Listening to the soothing hum and thump of yeast metabolism allows one to imaginatively project a listening body into the milieu of the yeast. Sound maps out the dimensions and characteristics of the acoustic space through which it is propagated: sound waves originating in one place extend outward in concentric circles, slackening their pace through liquid media, diffracting or reflecting off of walls and solid objects. These qualities of sound are utilized in sonar (sound navigation and ranging) to orient objects underwater. Sonocytology orients listeners to intracellular activity, clueing listeners in to the dynamism on the other side of the cell wall.

BUT CAN YOU DANCE TO IT? OR, HAPTIC CELLULAR SPACES

Having explored the ways cells become imaginatively embodied through sound, a complementary question arises: How does listening to the sound of cells affect a listener's understanding of the interior of her own body and its relation to noisy cellular bodies? Without falling into any tree-falls-in-the-forest quandaries, sound (as opposed to phenomena not defined by the limits of the animal sensorium, such as vibration) implies a listening body to hear it. The listener enters into the milieu of the cell and the vibrations resonate within the body of the listener. 'Sound invades us, impels us, drags us, transpierces us' (Deleuze and Guattari 1987: 348). The bodily proximity created by sound is acknowledged in culturally and historically bound analogies used to explain sonocytology: pressing your ear to a cell, or running your finger over its bumps and indentations. In this section, I examine the art that Gimzewski and Pelling have made using atomic force microscopy and sonocytology, attending specifically to how these exhibits relate listening to touching. Their work emphasizes the significance of physical exploration of cellular interiors and nanoscapes, blurring affective and scientific investigations into a sort of subcellular orienteering in which the cell is experienced as both interior and exterior to the explorer—as the 'deep space' of the human body and as an alien topology to be traversed.

Both Gimzewski and his graduate student, Andrew Pelling, collaborate with artists to develop visual art installations. Gimzewski has worked with Victoria Vesna on several technoart projects, including 'Nano Mandala,' in which they projected onto an 8-foot diameter circle of sand a video of a scanning tunneling microscope image of the molecular structure of sand mutating into an image of a mandala. They are also developing an ongoing series of interdisciplinary programs that explore intersections of nanotechnology, art, and culture. Their most recent work, NANO, was exhibited at the Los Angeles County Museum of Art in 2003 and 2004. The interactive exhibit placed viewers in fabricated intracellular spaces 'designed to immerse the visitor in the radical shifts of scale and sensory modes that characterize nanoscience' (Hayles 2003).

Gimzewski invented a new technique that uses touch to create an image and converts the data gathered through touch into sound rather than an image. He and Victoria Vesna explain scanning tunneling microscopy[xvii] in a coauthored article in *Technoetic Arts*:

The Scanning Tunneling Microscope represents a paradigm shift from seeing, in the sense of viewing, to tactile sensing—recording shape by feeling, much like a blind man reading Braille. The operation of a STM is based on a quantum electron tunneling current, felt by a sharp tip in proximity to a surface at a distance of approximately one nanometer (Gimzewski and Vesna 2003).

Or, as Andrew Pelling has explained it: 'We have recently discovered that information regarding the metabolic state of living cells can be gained from *feeling them in real time*' (Pelling 2004, emphasis added). The only aspect of the atomic force microscope that he changed was that instead of moving the probe over the surface of the specimen, he held the probe in place so that it could record the movements of the object beneath it. To elicit information from a space that is not visually accessible requires an engagement with acoustic and tactile signals, as Deleuze and Guattari observe:

Visibility is limited; and yet there is an extraordinarily fine topology that relies not on points or objects but rather on haecceities, on sets of relations (winds, undulations of snow or sand, the song of sand or cracking of ice, the tactile qualities of both) (Deleuze and Guattari 1987: 382).

The acoustic and tactile signals do not point to any static material state of the object of study, but rather represent the relations between things and the way objects are situated within milieus: listening to the cells makes biologists pay attention to how they respond to small differences and changes in temperature and osmolarity.

In the LACMALab art studio, a part of the NANO exhibit, visitors' full sensory engagement with nanoscopic space is reinforced through the use of molecular modeling kits. To interact with a three-dimensional molecular modeling program, viewers don 3-D glasses and use a wand to create crystal lattices whose nanoscopic structures are built in 3-D space and projected onto a blank wall. Amateur nanoarchitects can manipulate molecules, turning and shaking their created crystals using a pair of wired tongs. Taking literally his metaphor of the AFM probe as a small finger, Gimzewski developed another interactive program that translates the forces and displacements of the AFM cantilever into sensory information so that visitors can use their hands to explore the textures and vibrations of the surfaces of atoms and molecules.

Gimzewski's and Pelling's art projects are an extension and instantiation of the colorful metaphors they use to describe sonocytology. The imaginative flights elicited by sonocytology often center on changes in scale: cells are magnified until they appear at human scale in the form of 'passing freight trains' or 'living factories.' More commonly, the people listening to cells or operating the atomic force microscope are imagined as miniaturized so that they may inhabit and explore the nanoworld. While metaphors used to explain sonocytology frame imperceptible entities in familiar terms, the experience of listening to sonocytology does not naturalize the nanoworld and render it banal; on the contrary, the discourse of sonocytology aims to project listeners into a virtual reality in which they can explore alien landscapes.

The mysterious nature of the cell is written into its etymology: *cell* is derived from the Latin *cella*, chamber, from the Indo-European root *kel-*, meaning to cover or conceal. The alternate meanings of *cell* speak to this semantic residue: it is a room in a monastery, nunnery, prison, or mental institution, a room inhabited by a hermit or solitary, a grave, or, more recently, a political cabal with clandestine aims (OED). That is, a cell is a liminal space inhabited by a person who is either voluntarily or forcibly isolated from his or her society; it is a space for personal reformation, reflection, and transformation. Projecting oneself into such a space, then, can take on the mystical qualities of a spiritual journey.

According to anthropologist Arnold van Gennep's articulation of rites of passage (1960), after being separated from his or her society and before being reintegrated, an individual enters a liminal space in order to undergo a transformation. Media theorist Julian Henriques (2003) compares auditory spaces to liminal spaces; I'd like to think of them as zones of cultural transduction. Similarly, Deleuze and Guattari describe the places in which initiatory journeys take place as thresholds in which humans are in states of becoming-animal and becoming-molecular, 'from the howling of animals to the wailing of elements and particles' (1987: 249). In these thresholds in which transformations occur, 'a fiber stretches from a human to an animal, from a human or an animal to molecules, from molecules to particles…' (249).

Andrew Pelling, together with installation artist and musician Anne Niemetz, produced 'The Dark Side of the Cell,' the first concert performed entirely by yeast cells, which premiered at the LACMA gallery's NANO exhibit in June 2004 before being moved to a permanent installation at the UCLA Department of Design and Media Arts. The concert's title, an allusion to Pink Floyd's 1973 album *Dark Side of the Moon*, reinforces the association of the cell with an otherworldly lunar landscape. Furthermore, just as the 'dark side of the moon' cannot be seen from Earth, the title alludes to the visual inaccessibility of the cell. In doing so, the artists align the cellular noises with pop cultural 'reference points to help us identify sounds that are exotic, strange, and alien' (Johnson and Lecusay 2005). To make the concert an 'acoustically immersive space,' Pelling and Niemetz designed eight sculptures evocative of the cytoskeleton of cells onto which images, video, and sonograms of the performing yeast cells were projected. The twenty speakers installed throughout the darkened ersatz cellular space made each listener's experience different, depending on where in the room one stood. The audience was encouraged to move throughout the space to hear the concert from different positions. With 'no stage, performer or other particular center point of attraction' (Niemetz and Pelling 2004), the room was a smooth auditory space in which each listener was centered in her own immersive milieu, 'wandering in the space of messages filled or stripped of sense' (Serres 1998).

The analogies of hearing and touch come thick and fast in accounts of sonocytology, as does the metaphor of acoustic immersion. Take this description of an exhibit from the NANO show's catalog:

> The interior environment of the Cell provokes a challenge to the visitor's senses, complicating bodily perception and comprehension of scale. Pervasive computing techniques…create an immersive environment that elicits 'chemistry' between the human visitors, exhibition robots, and molecular representations. Inside the cell, visitors experiment with a large-scale projection of buckyballs programmed to respond to the touch of the visitor's shadow. Subtle action affects the buckyballs, replicating atomic behavior.
>
> This virtual and metaphoric cell-space provokes visitors to discover through physical engagement, to learn by feeling. Visitors can experience the act of manipulating atoms and encounter the effects of their bodily movements on the surrounding space. Physical movement triggers reaction from the environment of the Cell, creating 'gravity waves' on the floor and setting off sound effects. Everything within the space responds to touch and thereby encourages experiential learning and discovery…. The main sound feature of the inner cell is a deep, pulsing bass. The heartbeat of the installation. The interactive buckyballs projected onto the cell's walls emit a chiming sound that compliments the bass frequency. The surrounding sound immerses the visitor into the world of nano (Hayles 2003).

Crucial to understanding a cellular environment, according to the artists in the NANO exhibition, is physical engagement—entering into a domain in which one can manipulate cellular objects and be affected by them in a sensory feedback loop. In order to foster such an embodied engagement with cells, Vesna commissioned dancers to perform choreographed and site-specific improvisational dances within the NANO exhibit. As the dancers twirled within the cellular interior, images of buckyballs were projected onto their bodies. Steven Connor describes the 'intersensoriality' of 'the relations between sound and touch' as 'mimetic: touch accompanies, mimics, performs sound, rather than translating or defining it. Touch doubles sound rather than dubbing it' (Connor 2004). Touching, or grappling with, the cellular, is the tactile counterpart to the technically mediated experience of listening to the cellular.

Listening assumes two or more bodies in relation to one another. The decentered objects that occupy smooth space, Deleuze and Guattari note, 'can be explored only by legwork' because 'they do not meet the visual condition of being observable from a point in space external to them' (1987: 37). Hearing, then, implies touching, an intimate relation of vibrating and listening bodies. Moreover, any scientific examination of such a landscape requires that one take an imaginative leap into it, so as to explore it 'by legwork:' to access a smooth space requires that one 'occupies, inhabits, *holds* that space' (1987: 381, emphasis added). Or as pathologist and author Frank Gonzalez-Crussi describes it, 'in perceiving, our whole body vibrates in unison with the stimulus…hearing is, like all sense perception, a way of seizing reality with all our body, including our bones and viscera' (Gonzalez-Crussi 1989, qtd in Feld 2005: 184). To span the gap between observer and observed through touch is a step towards interacting with the cell as subject—but to *grasp* a biological landscape is at once to touch, to understand, and to seize it.

Soundscapes are zones of transformation in which bodies are 'transpierced' by sound and listeners are imaginatively projected into dynamic biological spaces. Natasha Myers relates depth, movement, life, and affect in her ethnographic analysis of biologists using interactive protein modeling programs, arguing that tactile techniques of analyzing proteins yield an 'embodied imagination' of the objects of study. She suggests that the root of the affective relationship with four-dimensional protein models is their movement and depth: by performing a sort of liveliness, protein models incite an affective and bodily entanglement, or 'mimetic transduction' in their users—'if it moves…then *we can move with and be moved by it*' (Myers 2006: 10, emphasis in original). How does the vitality of cellular life, as conveyed by cellular sounds and the substantive milieu and interior temporality such sound assumes, resonate physically and emotionally in the bodies of listeners? How are cellular interiors imaginatively embodied and enacted through sound, and how do these new modes of imagining cells affect listeners?

Deleuze and Guattari use *milieu* to describe the space in which the model of nomad science operates: nomad science thinks in terms of hydraulic models rather than models of solids and is concerned with flows of matter. 'It operates in an open space through which thing-flows are distributed, rather than plotting a closed space for linear and solid things' (Deleuze and Guattari 1987: 361). Smooth horizonless space, which Deleuze and Guattari compare to a desert or ocean, has no center and is 'occupied without being counted' (1987: 361). A good nomad scientist, Gimzewski tinkered with the atomic force microscope, repurposing it to record the vibrations of cells rather than to run a probe in raster fashion across the surface of the specimen. That is, instead of 'plotting a closed space for linear and solid things,' Gimzewski recorded things in flux. The milieu of the cell and the soundscape built by listening to cellular sounds (for example, the space in which the symphony was performed) are decentered smooth spaces in which each point differs slightly from every other point, 'a space of smallest deviation' that 'has no homogeneity' (1987: 370).

Nomad science is marked by feelings 'projected violently outward' from the interior body and 'into a milieu of pure exteriority,' transforming the nomad into something else: what Deleuze and Guattari refer to as 'becoming-woman' or 'becoming-animal' (1987:

355). More than mimicry, the process of 'becoming' means the intimate associations formed between two species that are physically or genetically 'caught up in one another.' Deleuze and Guattari use this term to tangle the clean lines of descent represented in genealogical models of evolution. To listen to a cell knowing that its sounds index biological activity is to be made aware of its material conditions and interior processes—that is, its interior milieu and temporality. By listening to the space and time of an inaccessible and otherwise insensible object, listeners are projected into a cellular terrain and are physically and cognitively affected by grappling with the cellular. To explore an alien territory is both a lesson in extreme otherness and a startling reminder of the conditions of the interiors of our own bodies and cells.[xviii] The uncanny experience of listening to the interiors of cells is a rush of recognition flooding a shared acoustic milieu—a becoming-cellular of the listener.

CONCLUSION: CAN THE SUBCELLULAR SPEAK?

I end with a question inspired by Gayatri Spivak's foundational question, 'Can the subaltern speak?' Spivak interrogates the possibility of representing the consciousness of those denied subjectivity or a meaningful place within historical narrative. In doing so, she exposes 'the slippage from rendering visible the mechanism to rendering vocal the individual' (1988: 285) and calls for 'measuring silences' as the first step in calling forth the consciousness of the colonial subject. To ask the same question of cells draws attention to the ways in which, by recording cellular noises and comparing them to speaking, singing, or screaming, scientists represent cells as subjects capable of speaking to their own conditions. What sorts of cells are enacted by 'rendering vocal' their vibrations? To say that a cell is 'speaking' is to project cultural notions of what it means to be human, to be subjective and agential, and even of what it means for something to be *meaningful*, into the cellular milieu. Perhaps sonocytology is a mode of imperialism, seizing a cellular colony and asking that its epistemology resonate with our own. This possibility reminds us of the limits of scientific representations: to listen to a cell is always to speak for it.

Footnotes:

1. Serres, Michel. 1998 *Les Cinq Sens*. Paris: Hachette, p. 180-181. Trans and qtd by Connor, Steven in 'Michel Serres' Five Senses' in *The Sensual Culture Reader*, p. 324.

2. Cage, John. 1967. *A Year from Monday*. Middletown: Wesleyan University Press, p. 34. qtd. in Kahn, Douglas in *Noise Water Meat*, 195.

3. The trajectory of twentieth century biosciences and biotechnology is closely bound up with yeast, an organism with significant economic uses. Because of its abundance, economic and industrial significance,

and the wealth of scientific information on it, yeast is often at the vanguard of new scientific experimentation. Yeast was instrumental in the early development of the biotechnology industry. It was present when the Royal Swedish Academy of Engineering Sciences coined the first formal definition of biotechnology in 1943 to designate a new initiative of the Academy—created at the urging of the Secretary of the Brewing Research Society—that was devoted to pursuing biological solutions to wartime food, energy, and pharmaceutical shortages. Edy Valendar, an MIT-trained engineer, was named director of the new section. He proposed the name *biotechnik,*

To bring together applications which arise while one is learning to influence biological processes scientifically and exploit them technologically in an industrially organized activity, for example in industrial yeast cultivation, in the food industries for processing and improving the raw products as well as for the preparation and conservation of foodstuffs (Bud 1993: 96).

4. An earlier example of the disruption of laboratory work by sound is provided by Schmidgen (2002): Adolphe Hirsch, director of the Neuchâtel observatory in Switzerland, began to experiment with using chronoscopes to measure the reaction time of astronomers in 1861. Throughout his experiments, he was disturbed by the humming of his own lab instruments and by the ringing of bells outside. Hirsche's 'efforts to precisely determine and communicate time were threatened by another, more ancient system for communicating time' (259-260).

5. For more examples of 'oculocentric' terminology in science studies, see Mody 2005.

6. 'We took the AFM vertical deflection data straight off the photodiode and logged it as a 16bit ascii text file which was basically one column of vertical deflection values. The time between each value is then 1/f, where f is the sample frequency (typically 10kHz or more). Anyway, both Awave and SpectraPRO allowed us to just import these ascii files with the appropriate sampling rate and save them as wav. Since they are oscillatory they are just like any electronic sound file. The only manipulation was normalization to 12-16 dB which made the files louder. Otherwise all the frequency information and relative amplitude modulation was retained' (Pelling 2006).

7. To listen to recordings of cellular sounds, visit *The Dark Side of the Cell* website: http://www.darksideofcell.info/ (http://www.darksideofcell.info/)

8. Comparing the AFM to a record needle raises the question of whether a vibration constitutes a signal by virtue of its being audible. Poet Rainer Maria Rilke asked in 'Primal Sound' (1919), 'What variety of lines, then, occurring anywhere, could one not put under the needle [of a phonograph] and try out? Is there any contour that one could not,

in a sense, complete in this way and then experience it, as it makes itself felt, thus transformed, in another field of sense?' Friedrich Kittler responds to Rilke's question by pointing out 'Before him [Rilke], nobody ever suggested to decode a trace that nobody had encoded and that encoded nothing' (1986: 44).

9. Lily Kay notes in *Who Wrote the Book of Life?* that 'the language of life' is a metaphor imbued with 'operational force' which, although having a long history in Western culture, was made literal and given scientific legitimacy by linguistics only in the 1950s and 60s. In a Derridian turn, sonocytology extends the linguistic metaphor of life by listening for uttered signs rather than decoding written words.

10. C.S. Peirce defines three types of signs: the icon, the index, and the symbol. The index is a sign that has some kind of physical relationship to its referent. Or, as Peirce more lyrically puts it, 'Anything which focuses the attention is an indication. Anything which startles us is an indication, in so far as it marks the junction between two portions of experience' (Peirce 1894: 9).

11. The distinction between occurrences and events is one of awareness: the act of looking or listening turns something that just *happens* into something more momentous. Walter Benjamin coins the term 'unconscious optics' to refer to the camera's ability to bring a previously unnoticed movement to our conscious attention by substituting an 'unconsciously penetrated space…for a space consciously explored by man' (1936). Perhaps we could think of sonocytology as a technique of 'unconscious acoustics' with which vibrations too small to be heard are brought to our attention.

12. Anthropologist of science Stefan Helmreich uses multiple registers of *immersion* and *transduction* to anchor his ethnographic account of his descent in the underwater submersible *Alvin*: immersion can alternately be used to describe being submerged in water, letting sound wash over you, or the classic ethnographic experience of cultural immersion (forthcoming).

13. A fifth definition of transduction mediates between the technical and the biological: it refers to when a machine can predict new outputs based on prior experience of inputs and their resulting outputs, i.e. learning.

14. Henriques suggests that transduction surpasses traditional binary compartmentalizations of the world: 'A transducer is a device for achieving the escape velocity to leave the world of either/or and enter the world of either and both' (2003: 469).

15. Myers (2005) and Helmreich (2005) elaborate upon the acoustic and biological resonances of transduction to think through how biological objects and spaces are perceived through mediating technologies.

16. Deleuze and Guattari say of the relation of sound to matter: 'it is a question of a highly complex and elaborate material making audible nonsonorous forces' (1987: 95).

17. The scanning tunneling microscope and the atomic force microscope are both examples of scanning probe microscopy. The technique of drawing a probe over a sample to create a three-dimensional map of surface topography was developed in 1981 at IBM Zurich. Scanning probe microscopy affords a greater resolution than light or electron microscopy, and can also be used for nanolithography (the manipulation of atoms to build nanoscopic structures).

18. Yet listeners do not naturally recognize their own biology in the sounds made by cells—rather, such recognition must be taught, as Vesna and Gimzewski do in the NANO exhibit. Recognizing audition as a historically situated and culturally constructed process, sonocytology could be a technique that will condition listeners to imagine cells as substantial, dynamic, and environmentally situated entities.

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