Media and Prosthesis[1]

The Vocoder, the Artificial Larynx, and the History of Signal Processing

MARA MILLS

Vocal Codes

Fig. 1. Voder room, Golden Gate Exposition, San Francisco, 1939. Courtesy of AT&T Archives and History Center.

American Telephone and Telegraph (AT&T) commemorated the twenty-fifth anniversary of the first transcontinental telephone conversation with another telephonic event. On July 29, 1939, a tribute call was placed between the bicoastal World's Fair sites. Not much was said—the transcript records these ordinary lines:

> "Hello, San Francisco. Hello, everybody, this is New York speaking. Greetings to you in San Francisco."
>
> "Hello, New York. This is San Francisco. Greetings and best wishes to New York."[2]

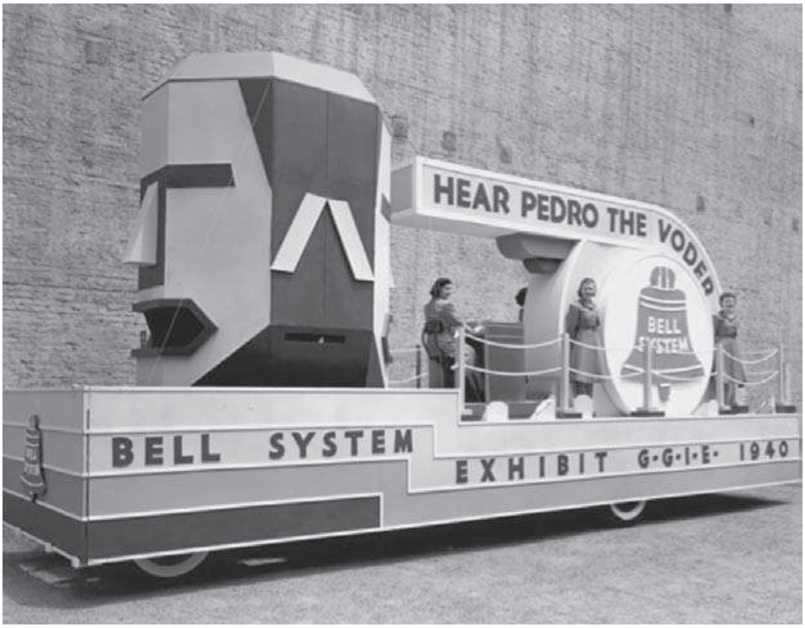

Fig. 2. Voder float at Golden Gate Expo. Courtesy of AT&T Archives and History Center.

What made this exchange extraordinary was that it took place between two talking machines—two Voders, or Voice Operation DEmonstratoRs. Bell engineers nicknamed these machines "Pedro" after the emperor of Brazil, who tested the telephone at the 1876 Philadelphia Centennial ("My God, it talks!"). The emperor became the emblem of naive astonishment in subsequent publications, which reminded readers, "The telephone didn't talk, it carried talk."[3] But with "Pedro the Voder," AT&T announced the arrival of the World of Tomorrow.

Advertised as the first technology to create true speech without recourse to film or phonographic recording, the Voder went beyond previous automata in its ability to turn out full sentences composed from any combination of sounds.[4] It furthermore produced assorted inhuman sounds, from a pig's squeal to a voice of impossible bass, all with an "electrical accent." Five million visitors attended the exhibit in New York alone; many had difficulty comprehending the new medium of speech synthesis. ("Is it true that there really is no phonograph record? . . . It's amazing!"[5])

The Voder was outwardly similar to a parlor organ. The white keys produced vowels; the black keys acted as "stop" consonants (such as *t* and *d*), cutting off airflow; and a foot pedal changed the pitch. In New York, AT&T vice president J. O. Perrine demonstrated the machine with the help of a "Voderette," one of twenty-four telephone operators who trained a full year for the World's Fair event. Their performances included slides that analogized the Voder's components to parts of the human vocal tract. Perrine told audiences that this technology might "enable mutes to talk." "Some day," he predicted, "it may be possible for a telephone circuit to have a narrow frequency band in order to transmit only the specifications for the voice. Then, we will talk into a transmitter, just as we do now, but the line will carry a signal to a device at the other end of the circuit which will recreate our words for the listener there."[6]

One of the Voder's most prominent spectators was Vannevar Bush, director of the federal Office of Scientific Research and Development. In the 1945 article "As We May Think," Bush proposed the Voder as one element of his Memex, a memory-extending desk or information-management system, which famously influenced Theodore Nelson's theory of hypertext. Bush saw in the Voder a technique for orally making, consulting, and *compressing* records, one that might supersede the time-consuming and "artificial" actions of writing and typing. Moreover these records could be automatically transmitted as electrical signals, interconverted between the senses, and displayed by multimedia machines:

> To make the record, we now push a pencil or tap a typewriter. Then comes the process of digestion and correction, followed by an intricate process of typesetting, printing and distribution. . . . Will the author of the future cease writing by hand or typewriter and talk directly to the record? . . . At a recent World Fair a machine called a Voder was shown. A girl stroked its keys and it emitted recognizable speech. No human vocal chords entered into the procedure at any point; the keys simply combined some

Fig. 3. Voder operator and interlocutor with test machine in San Francisco, 1939. Courtesy of AT&T Archives and History Center.

> electrically produced vibrations and passed these on to a loudspeaker. In the Bell Laboratories there is the converse of this machine, called a Vocoder. The loudspeaker is replaced by a microphone, which picks up sound. Speak to it, and the corresponding keys move. This may be one element of the postulated system.[7]

The Voder was an ornamental descendant of the vocoder, a machine that now appears throughout the fields of musicology and media studies as an exemplary "posthuman" technology, for its ability to give the voice a "robotic" inflection.[8] Recent theorists have used the vocoder as evidence for paranoid readings of militarized new media, as a model for the repurposing of military technology by artists and musicians, or as exemplary of the condition of virtuality.[9] More subtly, Alexander Weheliye presents the vocoded voice as a foil to the authentic, independent humanist subject, and—at the same time—he offers machinic voices from black popular music as an alternative to the white masculinity governing most posthumanist narratives.[10]

The significance of the vocoder to the history of technology goes beyond sound effects, however. Assembled by Homer Dudley at AT&T's Bell Laboratories in the 1920s, this machine promised to *remake* speech, to make communication through wire or air more efficient by compressing, coding, and ultimately re-synthesizing the voice. While electronic musicians have in turn remade and remixed the sounds of the early vocoder, AT&T engineers continued to develop new models, hoping to transmit *natural-sounding* compressed speech over the telephone. Between the 1960s and the 1980s, specifically, Manfred Schroeder and Bishnu Atal built a series of vocoders with fewer audible "artifacts" from signal processing. These "source coders" eventually enabled high-volume cellular telephony.[11] As Lisa Scanlon has summarized in *Technology Review*, "Every time you make a digital cell-phone call, you take advantage of speech coding—the process of converting human speech into a simpler signal that can be transmitted more quickly. This technology has its roots in a quirky organlike electrical speech synthesizer invented nearly 70 years ago by an AT&T researcher."[12]

James Flanagan credits the vocoder with helping to rethink the representation of speech, from the "facsimile waveform" or direct-transmission approach of the early telephone system to the "analysis-synthesis" or simulation method for coding and reconstructing speech.[13] While the early twentieth century witnessed many schemes for coding and processing speech signals, the analysis-synthesis approach built certain aspects of human communication into the telephone system itself (an example of what I have elsewhere called "ergonomopolitics"): "The goal is to determine the physical characteristics of speech production, perception and language and to incorporate these characteristics into the transmission system. As such, they represent information that need not be transmitted" (*SASP*, 244). Speech was to be dissected at the transmitter, with certain vocal elements subtracted and then re-synthesized at the receiver.

More broadly, the principle of imperceptibly eliminating "redundancy" from a message set a lasting standard for the coding of audio *and* visual material. Telstar engineer and science fiction author John Pierce called the vocoder "one of the special cases of highest importance" contributing to Claude Shannon's information theory. Dudley's colleague Lloyd Espenschied insisted that the vocoder "philosophy" underlay both information theory and cybernetics:

> In the last decade or so there has taken shape a new philosophic appreciation of what is involved in the conveyance of intelligence. . . . This philosophy is being expressed in such a book as Norbert Wiener's "Cybernetics," and papers by such as C. E. Shannon on A Mathematical Theory of Communication involving the conception of the code transmission of speech, the type of modulation employed in respect to the noise level, etc. Dudley's demonstration of the frequency contraction and re-expansion of speech was one of the underlying contributions to this modern renaissance in the conception of what is "information," and how it had best be transmitted.[14]

Dudley's "Signal Transmission" patent (2,151,091)—based on his vocoder research and filed in 1935—argued that speech contained both "variable" and "fixed" components, concepts that were clear predecessors to "information" and "redundancy." Dudley described the action of the vocal cords as "fixed": non-volitional and predictable. "The fact that the vocal cords are always used in the voiced sounds is a fixed feature," he reasoned, "and also the fact that they always vibrate in the same buzzer-like way." Hence this action could be incorporated into the receiver, rather than transmitted. In a 1994 interview with the IEEE History Center, Schroeder also rooted the more radical technique of perceptual coding in vocoder technology. "This compression business got applied to music. Today you see music compression all over the place, in a CD-ROM, the World Wide Web and so forth. Everything is compressed now." With perceptual coding, irrelevant material is removed before transmission—and never reconstructed.[15]

Dudley began working on "frequency range reduction" and the

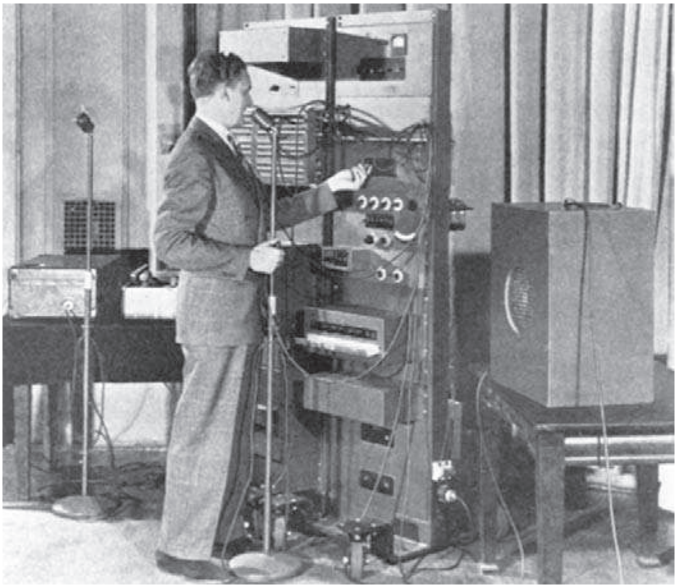

Fig. 4. C. W. Vaderson with the vocoder. Courtesy of AT&T Archives and History Center.

"compression" of speech in 1927, hoping to squeeze as many calls as possible through a proposed transatlantic telephone cable.[16] By 1935, this line of research would result in a functional vocoder, or "VOice-CODER."[17] The vocoder was made up of two main components, the first being an "analyzer" that transduced speech into an electrical signal, filtered it as a series of frequency bands, and then sampled each, transmitting only the fraction essential for intelligibility.[18] This sampling was meant to extract the "codes" of speech impressed upon the acoustic wave by the motions of the vocal tract, discounting the rest as redundancy. At the receiver, the vocoder's synthesizer re-created speech by passing these extracts, or "control signals," through two sources of noise. "In ordinary telephony," Dudley explained, "we move a sound wave electrically from one point to another by direct transmission but in the synthesizing process, only the specifications for reconstructing the sound wave are directly transmitted" ("SS," 98).

Efficiency was arguably a new, and modern, approach to the voice; however, the principles of compression and electrical synthesis had already been established by other branches of speech research. Dudley's project explicitly built on the history of lip-reading, artificial vocal tracts, and artificial larynges. In the eighteenth and nineteenth centuries these fields demonstrated that speech had a materiality of its own, distinct from alphabets and print; furthermore, speech could be divided according to the actions of the larynx and the articulators. In the ensuing language of telegraphy and wireless, the movements of the lips, palate, tongue, and teeth imprinted a "message" onto the "carrier" of the breath, which vibrated from its passage through the vocal cords.[19] For Dudley, the movements of the articulators—and their modulating effects—were themselves codes that might be subtracted from speech and sent with great efficiency over a telephone line, instead of transmitting an electrical current analogous to the voice in full. As for remaking speech at the receiver, years of artificial larynx research at AT&T had established a means of simulating laryngeal vibration using electrical circuits.

In what follows I will consider the politics of this technology transfer, namely, the movement of objects and techniques from the domain of "assistive" technology to that of mainstream engineering. Lip-reading produced information about the "parameters" of speech, new ways for the voice to be materialized and simplified. Artificial larynges and vocal tracts commenced the mechanization of speech, although in AT&T corporate accounts the artificial larynx is mostly depicted as telephone "by-product"—inscribing a dependency relation between engineers and larynx users.[20] Graham Pullin has recently argued against the "trickle-down" hypothesis of assistive technology, which considers disability to be too small a market for innovation.[21] Others have interrogated the very category of "assistive" technology (of which prosthesis is a subset)—a category defined, with circular logic, through use by people with disabilities.[22] To Richard Ladner, the phrase "has the ring of paternalism, a view that people with disabilities need lots of extra help, are dependent and are not capable human beings."[23] Katherine Ott has further addressed its redundancy: "Since all useful technology is assistive, it is peculiar that we stipulate that some devices are assistive while others need no qualification. Besides serving to stigmatize and segregate a benign and inanimate entity—a device or appliance—the term 'assistive technology' also needlessly complicates understanding of the devices so designated."[24] What Ott calls the "technological ghetto" of assistive technology is all the more striking when one considers "media" that bear a literal relationship to "prosthesis."

As famously demonstrated by Georges Canguilhem, the normal and the pathological were placed along a continuum by modern medicine, such that the latter began to be resourced for insights into the former. Likewise, as Henri-Jacques Stiker explains, disability began to be viewed as something amenable to rehabilitation. "For good or ill, the disabled were [previously] exceptions and stood for exceptionality, alterity; now that they have become ordinary, they have to be returned to ordinary life, to ordinary work."[25] This logic is also at work in the history of telephone engineering, where disability and the construction of prosthetics promised to reveal the mechanisms of speech and hearing, the essential elements of communication, and various automatic techniques for synthesizing the voice. Although the elements of speech, once understood, could be recombined to different ends—from making novel voices to optimizing normal speech—in the context of the telephone system, ergonomic efficiency generally took precedence.

In another register, this article explores the politics of modulation—the ideals of speech production and perception built into transmission systems, the imagined senders and receivers of messages, and the effects of signal-thinking on styles of communication. The information about speech generated by lip-readers and artificial larynx users circulated into a telephone system designed for statistically average users—a system that specifically excluded deaf people and those with atypical voices. This pattern is a routine of technical development; Gerard Goggin and Christopher Newell contend that even when disability is "invoked as a warrant for development of new technologies . . . too often the introduction of [these] new technologies can create new forms of exclusion for people with disabilities."[26] Outside the domains of music and entertainment, the principles of efficiency and universality central to the history of signal processing also worked to censure atypical voices and minor modes of communication.

Lip-reading

Frank Jewett, the first president of Bell Labs, explained in 1935 that *manipulation* was essential for electrical communication. "Mere transmission of electrical energy in any form does not provide electrical communication. It is the way we manipulate the electrical energy at the transmitting station which gives us our ability to communicate intelligence."[27] Electricity and sound were fundamentally similar in their wavelike behaviors; in the earliest version of telephony, an electrical current was varied to match the waveform of the original speech. As traffic increased along a limited number of telephone lines—each line, in turn, of limited bandwidth—engineers experimented with techniques for "modulating" the electrical signals that carried spoken messages. With computer automation in the 1950s and 1960s, the manipulation of signals became increasingly complex—and was increasingly described as "processing." The term *signal processing* was at first mostly applied to digital coding and vocoder-based compression. Frederik Nebeker, who has written the only history of this concept, explains that signal processing now refers broadly to "the changes made to signals so as to improve [their] transmission or use"—this includes everything from analog filtering to digital coding to synthesis.[28]

Experiments with the digital coding of signals began in the 1920s with pulse code modulation; while this early example of "processing" served many purposes—such as encryption, multiplexing, and signal integrity in the presence of noise—it did not result in compression. Espenschied contended that before the invention of the vocoder, there was "no way known whereby band[width] could be materially economized."[29] Dudley based the vocoder's sampling mechanism on the theory that tangible "gestures" lay beneath speech. An early spur for his insight about speech compression came from the lip-reading community, as Espenschied recalled in a Bell Labs memo: "One of Dudley's initial conceptions and arguments was this: there is such a thing as lip reading on the part of the hard-of-hearing. Therefore, it must be that the intelligence of speech is contained in large measure merely in the syllabic low-frequency modulations of the speech mechanism, without regard to the higher frequency components which normally render the speech to the ear."[30] Dudley theorized that much of the audible sound emitted from the throat was redundant and might be subtracted at the transmitter, then reconstructed at the receiving end of the telephone line. Only the parameters of the speech "gestures" needed to be transmitted.[31]

Several associations can be traced between AT&T and the world of lip-reading, the first having to do with the corporation's historical roots in the family history of Alexander Graham Bell. In the United States, oralists began teaching lip-reading in the 1870s, at places like Sarah Fuller's school in Boston—and the "School of Vocal Physiology" she invited Bell to open in the same city.[32] To teach both lip-reading and articulation, Bell made use of the Visible Speech system created by his father, Alexander Melville Bell. This "physiological alphabet" symbolized the positions of the lips and tongue and other vocal organs during the production of speech sounds.

The earliest treatises on the possibility of deaf education, dating to the 1600s, refer to the marvel of "ocular audition."[33] With the founding of deaf oral schools in the eighteenth century, most notably by the Braidwood family in England and Samuel Heinicke in Germany (formal sign language having evolved in the French context), lip-reading became systematized and inseparable from articulation training; it was the means for deaf students to imitate, as well as understand, the speech of others. Oralism, often linked to a broad philosophy of "universal" communication, prioritized conversation with the majority over fluency in a "minor" language such as sign.[34] Mabel Hubbard, a student of both Bell and Fuller (whom Bell eventually married), published an article in *Atlantic Monthly* on the exigency of lip-reading for deaf people. The hearing, she warned, preferred communication to be effortless and resented meeting deaf people halfway with pencil and paper: "Ladies and gentlemen, tradespeople and servants, all regard writing as something to be avoided as much as possible."[35]

Fig. 5. A, E, L (*top*), O, Sh, W (*bottom*). After losing her hearing as an adult, Cora Kinzie trained with Nitchie and Bruhn. She and her sister Rose (*above*) started the Kinzie School of Speech-Reading in 1917. Photographs courtesy of The History Factory and The Alexander Graham Bell Association for the Deaf and Hard of Hearing.

Until 1890, lip-reading in the United States was primarily learned by children in oral institutions. That year, Lillie Eginton Warren opened the Warren Articulation School for children *and* adults in New York City. At the outset Warren employed the 119 symbols of Bell's Visible Speech, but she soon designed what she called "a numerical cipher method." Detailed in her 1895 book, *Defective Speech and Deafness*, Warren reduced the sounds of English to sixteen facial configurations, which she then converted into numbers. "All words," she maintained, "are but rearrangements of the same elements." The long-standing phonetic concern to materialize speech was in this instance joined with efficient coding. As an aid to pronunciation, lip-reading not only allowed deaf people to participate in spoken conversation but also normalized their secondary communication differences for the benefit of the hearing world. Without articulation training, Warren believed, deaf people made "discordant sounds" and their faces were "disfigured by unpleasant and unnecessary movements."[36]

What kind of reading was lip-reading? Like machine reading, it was more often defined by scanning and pattern matching than by comprehension or interpretation. This transformation of dialogue into "reading" prefigures what John Durham Peters has called the signal transmission model of twentieth-century communication, which implies that communication ought to be a series of seamless one-way transfers. (Peters further argues that this model expects listeners to be "made over in one's own likeness and image.")[37] Lip-reading was one aspect of the rationalization of speech that took place in nineteenth-century phonetics and deaf education. All voices became reducible to physiology and technique, and speech was linked more often to automation than autonomy.[38] According to Karl Brauckmann, who headed a deaf school in Jena in 1900, the smallest unit of thought might be the word, but the units of speech were motions, performed without thinking at all:

> The organs of speech may be thought of as a machine—a speech machine, which, set going in one way, runs through a certain series of movements. . . . Two men face one another—two speech machines. One man speaks; the machine begins to move. The other man does not hear, but he sees some of the speech movements of the other, and at once his own speech machine begins to make these movements . . . and as his vocal organs execute the movements of the series he feels them; his speech sensations are the same as those of the speaker and as complete, and they enable him to understand. (*SLR*, 198)[39]

While some oralists, and some communication engineers, continued to embrace speech as uniquely human, others—like Dudley—believed it to be arbitrary; they privileged the voice only as a vehicle for convenient majority communication.

Fig. 6. "Means for Teaching Reading of the Facial Expressions Which Occur in Speaking." Lillie Eginton Warren, Patent 726484. Issued April 23, 1903.

By the 1920s, lip-reading insinuated itself even more directly into telephone engineering culture, via a series of affiliations between AT&T and the League for the Hard of Hearing. One of Lillie Warren's deaf assistants, Edward Nitchie, founded his own school of lip-reading in 1903, which expanded by 1909 into the New York League and by 1919 into a national advocacy and rehabilitation agency.[40] Members of the New York League pressured AT&T to divert some of its electroacoustic research to audiometry and hearing prosthesis. AT&T launched its own Department of Speech and Hearing in 1913, hoping to discover the average thresholds of human hearing and the range of the human vocal apparatus in the interest of streamlining the telephone system. Harvey Fletcher, whose father was deaf and who soon directed this department, was exceptionally willing to collaborate with the New York League. (By 1928, in fact, he was elected president of the American Association for the Hard of Hearing.) According to Dudley's laboratory notebooks, he too had direct contact with League members, exchanging information about publications and lectures.[41]

The League inaugurated a national lip-reading championship in 1926.[42] By the following year, Fletcher began serving as judge for the New York Metropolitan title, annually attended by crowds of hundreds. In 1930 he engaged a pair of lip-reading champions for his public unveiling of AT&T's new two-way television. As dramatically recorded in the *New York Times*, "Each of the subjects had before her in the booth's eerie twilight a 'televised' image of the face of the other, about one foot square. 'Aren't you thrilled,' Miss Pless asked the girl two miles away? The listeners caught Miss Parry's nervous laugh and heard her say: 'Now I can hear on the telephone.' She meant that she could see."[43] The ability to lip-read via television was surely a good advertisement for the clarity and instantaneity of television transmission. Lip-reading, too, seemed to promise that brand-new perspectives could be had without sacrificing communication norms or the social order.

The Nitchie Method instructed the lip-reader to "train his eye to substitute for his deaf ears," and Nitchie himself intended lip-reading to be a feat of translation, not one of passing.[44] He spoke out against the concealment of deafness, which he believed resulted from "a feeling of shame, as though we had done some wrong, that impels us to try to hide our failing ears."[45] Yet many deafened individuals turned to lip-reading precisely in the hopes of invisibility. Frances Warfield, a New York League volunteer, described reading lips as the ticket for getting "off Peculiar Street—a place of hand-cupped ears, ear trumpets, and queer black boxes."[46] Still others, such as essayist Persis Vose, resisted lip-reading because they felt that even this assimilationist technique "meant admitting deafness."[47]

As a decoding strategy, lip-reading was not without shortcomings. More than half of all speech sounds emerged from the recesses of the mouth and throat. *H* and long *u* were completely undetectable by the eye. Social historian J. C. Furnas, himself hard of hearing, complained in 1957, "Too many words—money, muddy, bunny, putty—look exactly alike on a speaker's lips and face. Some—uncle, cousin, sister, dinner—are invisible."[48] Lip-reading, he explained, was more properly called speech-reading, for it required attention to the entire face and neck. Earnest Elmo Calkins, an advertising executive who had studied with Nitchie, compared speech to handwriting: most of it was illegible, especially when the speaker had not been trained to enunciate.[49] Grace Barstow Murphy concurred that lip-reading should be thought of as dialogical, "a two-way affair, dependent both on the lip-reader's skill and on how the other person produces his words. If his lips are hard or rigid, without mobility, or if he swallows his words and is self-conscious, no one can read his lips."[50] Some people wore facial hair or heavy lipstick, others shook their heads or turned about while speaking, still others were too short or too tall. Murphy's husband, the naturalist Robert Cushman Murphy, mumbled impossible sentences ("That is a barnacle that grows only on a humpback whale")—until she insisted that he, too, attend speech training.

Lip-reading classes were laborious and dull, great bodily labor being required to maintain effortless conversation. In deaf oral schools, learning to read lips was bound up with the miseries of "articulation training." Children sacrificed years of content-based instruction in order to rehearse monotonous speech-and-breathing exercises: place the tongue against the palate, just so; position the lips to blow a feather, a candle flame, or a toy boat. In his 1930 memoir, *The Deaf Mute Howls*, Albert Ballin granted that "deaf-mute" people often had more success with lip-reading than did "semi-mutes." Articulation, on the other hand, was a trap of malapropisms, arbitrary spellings, accidental obscenities, and other opportunities for "oral failure." No deaf person, he insisted, had ever successfully passed as hearing. He recalled of his own lip-reading instruction: "The 'R,' 'Ng,' 'X,' etc. were so modestly concealed within the throat that I thought I should dive into my teacher's mouth to locate them. This entire process or method was both tedious and discouraging. I might also add that it was a bit disgusting when the teacher had partaken of onions."[51]

Dudley eventually recognized these limitations of lip-reading. He commented in 1955, "The lip reader would need X-ray vision to see enough of the moving parts to permit a complete and therefore accurate interpretation of speech. . . . The fact that the tongue, uvula, etc. are concealed is what makes lip reading so difficult and uncertain for the person who uses it."[52] Likewise, Dudley found that he could neither describe nor quantify all the vocal tract movements of English speech.[53] For the first functioning model of the vocoder, completed in 1935, he thus settled for a less radical compression, based on sampling features of the speech spectrum. The analyzing component of this vocoder filtered telephone speech into ten frequency bands. It then extracted the "parameters" of each band by taking a small (twenty-five-cycle) sample of power level or amplitude. These "control currents," along with a measurement of overall pitch, constituted the transmitted signals—greatly compressed as compared to direct transmission of speech. Throughout his publishing career, Dudley continued to use lip-readers and "silent talkers" to illustrate his basic concept—that the carrier could be separated from the message in speech.[54] And later models of the vocoder would return to articulation, the gestures of the lips and other vocal organs.

The Artificial Larynx

The vocoder incorporated models of human hearing as well as speech, both greatly streamlined. "The overall process," Dudley explained, "uses electrical circuits to copy a man repeating speech as he hears it."[55] He compared the "analyzer" to the human cochlea, which dissected sound into its spectrum. In this way, the ear recognized (or "de-modulated") the different timbres of speech, caused by the modulations of the vocal tract.[56] If the earliest version of the telephone was based on the middle ear—what Jonathan Sterne calls the "tympanic principle" for using a diaphragm to vary an electrical current—this new method of analysis-synthesis telephony would shift its focus to the inner ear.[57]

Lip-reading had indicated radical possibilities for speech compression, by suggesting that only the elements related to speech "information"—determined after the analysis phase—need be transmitted. At the receiver, speech could be re-synthesized by replacing the "fixed" elements with a rapidly vibrating electrical current, in turn modulated by the transmitted "control signals." In a 1936 issue of *Bell Laboratories Record*, Dudley discussed the origins of the speech-synthesizing component of the vocoder: "The first important step toward speech producing was the development of the artificial larynx. The device is entirely mechanical and produces a complex sound wave by an operation basically similar to that of the vocal cords. In the present system the element equivalent to the vocal cords is entirely electrical, and produces an electrical current" ("SS," 99). Artificial larynges were mechanical, and later electrical, analogies of the vocal cords. They relied upon the divisibility of the larynx and the articulators—the principle that the vocal tract could modulate any sound stream, even one substituted in by an artificial source.

"Prosthesis" has become one of the most acute points of contention between disability studies and media studies, yet it has an unavoidable place in the history of speech coding. From the first telegraphers to Ray Kurzweil, electrical engineers have described communication technologies as prosthetics that augment human sensory capabilities. Media theorists have adopted the same language, to miscellaneous effect. Marshall McLuhan, famously, defined media as "extensions," which in some cases caused *auto-amputation*—either a diminishing of innate capacities, or disability from overstimulation.[58] Hal Foster and Mark Seltzer have extensively analyzed this "double logic of prosthesis" in the humanities, with technology cast, in Foster's words, as a "demonic supplement, an addition to the body that threaten[s] a subtraction from it."[59] For some media theorists, the prosthetic signals artificiality and surrogacy, the threat of disability. Others, like Bernard Stiegler, use "prosthesis" as a synonym for "technics" to underscore the intimacy between bodies and technology: the externalization of human capacities, the essential nature of technical development to human being.[60]

Disability theorists have indicted these analogical and philosophical uses of prosthesis. Vivian Sobchak critiques the prosthesis-as-extension metaphor for eliding both the normalizing and the painful aspects of such appliances.[61] Most prosthetics fall into the category that I call *enjoining objects*, for they at once prescribe and prohibit a given conduct or condition—in the case of artificial larynges, "normal speech." S. Lochlann Jain has critically revised "the double logic of prosthesis," arguing that the same technology is often differentially applied; "it usually is not the same body that is simultaneously extended and wounded."[62]

It is impossible to make universal claims about feelings of woundedness or empowerment in relation to prosthetics. Individuals have different degrees of freedom to use personal technologies as "extensions"; moreover, these devices have numerous functions beyond extension and injury. It *is* possible, however, to generalize about the technical relationship between communication "aids" and "media." The case of the artificial larynx forces a rethinking of prosthesis in terms of compression—an extraction of the fundamental elements of communication. The editors of the recent anthology *The Prosthetic Impulse* remind readers that "prosthesis" was originally a grammatical term for adding an extra syllable to a word; it then moved into medicine as a replacement or an enhancement.[63] The remaking of speech, from artificial larynges to digital voice models, has to the contrary emphasized reduction—the elimination of frequencies from phonemes, the restriction of sounds to their parameters.

In the late 1920s and early 1930s, to determine the parameters of speech as well as techniques for its reconstruction, Dudley studied textbooks of phonetics and speech pathology, as well as the history of speaking automata.[64] In a retrospective article for *The Journal of the Acoustical Society of America*, published in 1950, Dudley placed the vocoder within a genealogy headed by the first successful attempt to mechanically generate speech—that of Baron Wolfgang Ritter von Kempelen in the eighteenth century.[65] Manfred Schroeder, years later, would credit von Kempelen with founding signal processing, and Dudley with initiating speech compression. Von Kempelen recognized the modifying actions of the vocal tract upon speech; the voice did not emerge fully formed from the throat.[66] This historical referent helps explain the etymological passage of the term *modulation* from singing and speech inflection to the shaping of electrical signals. Early modern speaking machines were entwined with deaf education, on the rise in the same years.[67] Deaf individuals were the imagined users of von Kempelen's and other artificial vocal tracts, which might speak for them, or allow them to see and feel the motions of articulation. It was thought that deaf children, in a related manner, could be "mechanically" instructed to speak.

If artificial vocal tracts demonstrated that the sound wave could be separated from its modulation, then artificial larynges offered a means for generating those complex waves. Richard Riesz, who designed the circuits for both the analyzer and the synthesizer of Dudley's vocoder, had previously coordinated an "artificial larynx project" at AT&T, building mechanical, and eventually electrical, analogies of the vocal cords. Perhaps surprisingly, AT&T was the first company in the United States to manufacture these devices. The president of Bell Labs, Frank Jewett, initiated the project in 1925 when one of his friends developed throat cancer and could not find an artificial larynx, despite having met someone with a prosthesis from Spain.[68] (Most likely, that prosthesis was the celebrated model designed by Tadeo Pereda, a man from Almansa whose own larynx had been removed.)

The larynx was a relative latecomer to the field of prosthesis, as the *New York Times* reported in 1887:

> False noses are not uncommon. False outer ears have been often appended to diminished heads so naturally that detection

> of the artifice has been difficult. In the matters of teeth, hands, arms, legs, and feet machinery has been made to take quite comfortably the place of natural organs and, recently, the attempts to replace lost human eyes have given a color of possibility to Munchausen's wild story of sitting down accidentally, in a coach, upon a live eye which was journeying, all by itself, to an adjacent village for treatment. The human larynx, however, has been considered beyond the domain of mechanical science.[69]

European instrument-makers had begun custom-making larynges in 1873, the year Christian Billroth performed the first successful laryngectomy. The early days of this surgery were forbidding, leaving only the rare survivor in need of rehabilitation.[70] The artificial larynx was thus a response to a condition at once physical and social, one caused as a by-product of modern surgery.[71]

The first artificial larynges offered new media and channels for speech communication, as well as strikingly new voices. Over time, these representations inched closer along the continuum toward normative speech. Based on the principle of the harmonica, many of the early models consisted of a vibrating reed inside an air tube. In a 1940 review for the *Illinois Medical Journal*, W. L. Hanson compiled impressions of the nineteenth-century voices that had spoken through experimental reeds of ivory, horn, silver, and cane: one from Spain gave a "high pitched, squeaky, unpleasant, unnatural voice"; another produced a "musical and singing tone, very disagreeable to the ear."[72] In 1899, brief mention was made in the *New York Times* of a larynx that looked like a metal whistle and caused its owner to speak with the voice of a "girl of thirteen or fourteen rather than that of a grown man."[73] This last prosthesis engendered its own set of gender impairments. Hanson criticized most of these devices for being "embarrassing, burdensome, delicate, difficult to repair" ("NALHR," 484).

Many people fashioned their own prostheses, and some delighted in experimenting with them.[74] Alexander Graham Bell reported, in *The Mechanism of Speech*, on a machinist in Glasgow who "employed his spare time in manufacturing reeds for himself. He had quite an assortment for experimental purposes. . . . He could change his voice from bass to tenor, and from tenor to soprano at will, by employing suitable reeds."[75] As late as 1936, Mr. Thomas Loring, an American mechanic, could be found demonstrating the larynx he built for himself, which included sliding parts to alter pitch, and a police officer in St. Louis was equally renowned for the larynx he assembled from a car horn and a clarinet reed.[76]

Describing the suicides that often followed successful laryngectomy operations, Paul Holinger has argued, "Loss of voice was regarded by many as more terrible than loss of limb or sight, or of life itself."[77] Dr. John Edmund Mackenty of the Manhattan Ear and Throat Hospital was one of the most outspoken American advocates of the surgery in the first decades of the twentieth century. Through a combination of antisepsis, one-stage surgical technique (following the method of the German surgeon Themistocles Gluck), and aftercare, he reduced the prognosis to 2 percent mortality.[78] Even so, Mackenty believed that too many people continued to avoid the surgery. "Loss of speech is the serious drawback in total laryngectomy, and turns many patients toward radium and the less radical avenues of escape. Radium is at present on trial. So far in my experience, it has proved very ineffectual, beguiling many to their death."[79] To remove this obstacle, Mackenty planned a new artificial larynx, one that sounded "human" and had pitch control. Yet he was unable to find a company willing to build the prosthesis; "the answer was always that it would not be commercially possible."[80] Even with the improved laryngectomy procedure, there were no more than six hundred people living without larynges in the United States in 1926.[81] When he learned that AT&T had launched an artificial larynx project, Mackenty submitted his designs.

He was invited to collaborate with a team that included Riesz, Harvey Fletcher, Charles Lane, and Robert Wegel. Their first model, the Western Electric 1-A, consisted of a rubber tube that connected the throat stoma to a silver mouthpiece containing a rubber "vocal cord." The tension of this vibrating membrane could be adjusted with a screw, to control pitch. Hanson recorded that the Western Electric larynx "delivered a low-pitched, somewhat guttural but strikingly human voice" ("NALHR," 484). The instrument conveyed streams of vibrating air into the vocal tract, upon which a speaker mouthed words as usual. In 1929 they released the 2-A, which made use of a metal reed for greater amplification.

Mackenty and Riesz gave out free prototypes and corresponded with volunteers to guide their design process. Riesz wrote to one man, who had tried both an experimental model and its subsequent commercial version, “You say you do not like the quality of the tone as well as you do that of your experimental model. I wonder if you can describe to me just what the difference seems to be and why you like the experimental model better. Adverse criticism is as welcome as any other kind—we can’t make progress unless we have accurate data to work on.”[82] Volunteers received initial training at the Bell Telephone medical center, after which they were sent off on their own. Some retrofitted their larynges; others took them to jewelers and accordionists for help with filing down the metal reeds or changing the length of the mouthpieces (usually in the interest of altering pitch).

Certain volunteers, such as a colonel hospitalized at Walter Reed, responded with no complaints:

> In using the larynx I have become almost a sensation around the hospital. I have given many demonstrations to medical officers individually and collectively and the unanimous verdict is that in developing such a device you have rendered an invaluable service to those of us who are unfortunate enough to require such assistance. I find the reed vastly superior to the original one and, now that I have had some practice, I am able to produce a degree of inflection. . . . It would be sheer cruelty to animals to require me to return the reed at once and reduce me to silence, sign making and scribbling after having had a taste of being able to express myself vocally.[83]

Outside the context of military heroism, others wrote with more ambivalence. Miss Grace C. H., for instance, described the awkwardness and pain of learning to speak with her prosthesis:

> It is just a week today since I have my artificial larynx. Every day I have tried it—I have to go very slowly as my throat is still very tender—and I think it is a wonderful invention. My people can

> understand some words very clearly & I find if I go very, very slowly it sounds better. I am mastering the air in the tube better too. The only thing that bothers me is the moisture gathering on the sound box, it soon fills up, but that I imagine is due to the condition of my throat rather than the new larynx. The tube in my throat which I wear constantly fills with phlegm & moisture many times a day & I have to clean it out.[84]

Most female users gave up on the first models entirely due to their "masculine" tone, a sound which indicated that male speech was the imperative, anyway.[85] Still other volunteers testified that they could not learn to use the device or simply preferred not to speak.[86] One physician reported that his patient found the artificial larynx prohibitively embarrassing, "because every time he tried to connect it with his throat, his operation was exposed and . . . it was a constant reminder to both those listening and to himself of his misfortune."[87] In this case, the artificial larynx had become a stigma symbol, doubling disability.

Through their years of involvement with the artificial larynx project, Bell engineers collected exhaustive details on speech production. Riesz added bellows to one larynx model and was able to experiment with it himself. He measured air pressure and rates of flow during speech, and calculated the harmonics present in the tones from various reeds.[88] Fletcher, according to his son, was similarly known to go "around the house with a bellows under one arm and a vibrating artificial larynx activated by the bellows, and analyzing speech sounds."[89]

When the larynx project was two years under way, Dudley began planning the vocoder, moving from mechanical to electrical analogies. As early as 1909, Themistocles Gluck had fashioned an ingenious "electrolarynx," using a phonograph recording of a vowel to vary an electrical current, which was then transmitted to a vibrating membrane worn in the user's nose or mouth.[90] And, in a 1922 experiment with which Dudley became familiar, John Q. Stewart had assembled an "electrical analogue of the vocal organs" at AT&T.[91] Comparing his endeavor to the musical analogies and model building of Helmholtz, Dayton Miller, and Edward Wheeler Scripture, Stewart realized that "a functional copy of the

Fig. 7. Riesz using artificial larynx with bellows.
Courtesy of AT&T Archives and History Center.

vocal organs can be devised which depends upon the production of audio-frequency oscillations in electrical circuits" ("EAVO," 311).[92] Using a buzzer as a sound source, he interrupted its electrical current periodically in an attempt to simulate the action of the vocal cords on an airwave; he had some success with reproducing voiced vowels.

In 1929, Robert Wegel, who took part in the Artificial Larynx Project, more thoroughly analogized the vocal cords to electrical vibrators—from door buzzers to microphones. Based on measurements taken from larynx models, he translated the physiology of this organ into the figures of circuit diagrams, concluding that "analytically the mechanism [of the vocal cords] is the same, and physically, closely analogous to that of the vacuum tube oscillator."[93] By the 1930s, Dudley was reading Victor Ewings Negus's

The Mechanism of the Larynx, and Riesz was working on an electrical prosthesis.[94] Together, the three men began assembling circuits of electrical oscillators and filters to simulate the vibrations and resonant modulations of human speech.[95]

To remake speech, the vocoder required a "simplified equivalent of the human vocal system" ("AS," 378). Its synthesizing component, to which the "description" of articulation was passed, offered a functional simulation of human vocalization:

> All of the important elements of the vocal system have electrical equivalents. . . . The steady power supply is essentially from batteries instead of compressed air in the lungs. The vibrating elements are a buzzer-sounding relaxation oscillator for the vocal cords and a resistance noise for the unvoiced sounds produced at the constriction in the mouth. Resonance, which determines the frequency components to be favored and those to be discriminated against, is provided by tuned electrical networks instead of air chambers as in the mouth. ("SS," 102)

The synthesizer thus replaced the breath with an electrical hiss and the vocal cords with an electrical buzz; any transmitted "control signals" would modulate these sound streams back into the unvoiced and voiced sounds of the original speech.[96] The early models of the vocoder were more or less intelligible, but pitch—correlated to the "naturalness" of speech—remained an ongoing problem.[97]

Digital Analogies

If lip-reading and nineteenth-century vocal tract models had indicated ways to extract the fundamental information from speech, experiments with artificial larynges underscored the complexities of reconstruction. For popular audiences, Bell engineers capitalized on the uncanniness of their artificial voices—their failures at normalization. For one thing, they demonstrated the larynx on *Robert Ripley's Believe It or Not!* radio show in 1935. During another media event, Sergius Grace, an assistant vice president at Bell Labs, used the larynx to communicate via radio with a plane flying over New Jersey, exploiting its artificiality to emphasize the achievements of modern communication and transportation technology.[98] After Grace performed for the New York Electrical Society in 1930, an audience member asked if "the dumb" could learn to speak with the larynx.[99] "Dumb" was by then a capacious term, referring to automation (as in the case of "dumbwaiters") as well as to muteness in humans. With the proliferation of speech synthesizers, however, automation was becoming compatible with speech.

Most users of the artificial larynx remained dissatisfied with its "mechanical" sound. In 1944, Captain C. N. Ingraham of Seattle remarked on his success with the *information* aspect of communication, "I seldom fail to make myself understood without difficulty. The exceptions are probably mental on the part of a listener who does not expect the sight or sound of the artificial voice."[100] This voice which distracted listeners from its message was marked by a low, monotone pitch and limited inflection.[101] Similarly, the vocoder had an "electronic accent" that made it unacceptable for everyday telephone use. By 1945 Dudley conceded that compressed speech was a distant goal for the telephone system, since voice coding resulted in *impairment*: "The pitch impairment [is] so objectionable as to make further work . . . unwarranted until such time as the pitch [is] greatly improved."[102] In the meantime, Dudley suggested the vocoder as a means to give voice to machines or animals on radio shows and in animated films:

> For the vocal-cord tones of the original, the Vocoder substitutes the output of a relaxation oscillator. But any sound rich in harmonics can be used: an automobile horn, an airplane roar, an organ. In some demonstrations, the sound, taken from a phonograph record, replaces the buzz input from the oscillator. Keeping careful time with the puffs of a locomotive, the demonstrator can make the locomotive puff intelligibly "We're—start—ing—slow—ly—faster, faster, faster" as the puffs come closer together . . . or a church bell may say "Stop—stop—stop—don't—do—that."[103]

Despite its unnatural sound, the vocoder was called to service for speech encryption during World War II. Winston Churchill and Franklin Roosevelt secretly communicated via a vocoder-telephone link; this "Project X" further inspired Alan Turing's "intelligent" enciphering machine, Delilah.[104] Within the X-System, vocoded speech was quantized using pulse code modulation (PCM) and then encrypted using a "one-time pad"—the message was masked with a recording of random noise, which was then "subtracted" via a matching phonograph record on the other end of the line. Engineers and historians of cryptology have for this reason placed the vocoder "at the beginning of the digital transmission age" as the first successful application of PCM.

Although examples of PCM date to the first two decades of the twentieth century, the technique was successfully developed by Alec Reeves for the French telephone system in 1937, as a means of transmitting signals without distortion under noisy conditions. As David Robertson notes in an article about Reeves, PCM created its own radical shift in the representation of speech:

> Reeves formulated the principles of pulse-code modulation—laying the foundations for all of today's digital and multimedia technologies. Rather than the analogue "voice-shaped current" used to represent speech since Bell's invention of the telephone in 1876, Reeves proposed that sound be sampled at regular intervals, with the values of these samples represented by binary numbers and transmitted as unequivocal on-off pulses.[105]

This early means of digitizing began with speech coding and moved into visual applications, becoming the predominant means of digital signal processing by the 1970s.[106] Early PCM required greater bandwidth than did analog telephony; its purpose was resilience rather than compression. Paired with the vocoder, however, another representational shift resulted—much of the content of speech was discarded by the time the samples were quantized. (This content could be reconstructed at the receiver, in the case of "lossless" systems, or it could be permanently left behind, in the case of "lossy" reproduction.) In the X-System, the vocoder's analog samples were themselves sampled in time, with different patterns of electrical pulses assigned to code the associated amplitudes.

In 1955, John Pierce asked Manfred Schroeder to return to the vocoder principle, attempting "analysis-synthesis" for the transmission of *high-quality* telephone speech. Schroeder began working on a "voice-excited vocoder" which transmitted "part of the speech signal . . . uncoded" rather than attempting to accurately measure the changing pitch of ongoing speech (*CS*, 36). In the 1960s, he and Bishnu Atal—greatly aided by new digital computers—devised linear predictive coding (LPC), a method for "predicting" new speech samples based on previous series. LPC led to the relatively imperceptible compression now found in mobile phones and Internet telephony.[107]

As Schroeder later explained, "Much of speech compression is based on source coding. This means that the compression strategy is based on the characteristics of the human vocal apparatus and the constraints it imposes on possible speech signals" (*CS*, 126). A series of analogies thus runs from the human voice to mechanical models to electrical oscillators and filters and finally to digital codes. The materialization of the voice, the separation of the larynx and the "modulators," and the translation of speech into wood and rubber shifted into *functional* mechanical and electrical models and finally into analog and digital "descriptions" of speech. By the twentieth century, the voice itself was redescribed in the language of electrical engineering, and analogies from this industrialized voice would expand to include all forms of electrical communication. In 1945, John Mills compared all signal transmission—fax, radio, television—to speech, the general principles being "generation of a current. . . . its modulation to put in the signal, its transmission, and its demodulation to recover, to re-create, the signal."[108]

Lip-readers, artificial larynx users, and acousticians alike investigated ways to materialize speech, translate it into different media, break it into simple components, or synthesize it from diverse materials. Telephone engineers drew on this research to deduce the absolute minimum parameters through which speech could be transmitted and remade. Today, rather than directly reproduce speech, transmission and recording systems increasingly contain simplified models of speech and hearing; they code and compress speech based on an understanding of the elements that are redundant—those that can be eliminated and later reconstructed—as well as those that are irrelevant to the human ear. Prior experiments in the name of rehabilitation (or, less commonly, play and the invention of new voices) have been reframed within the paradigm of efficiency, specifically the maximization of norms. This is not a linear history, then, but instead a series of *remediations*—a double-barreled word in the context of disability history.

When ideas about bodies are built into digital signals, these signals, in turn, produce bodily effects. At an extreme, some speech coding now excludes individuals with the very differences that helped engineers map the parameters of speech production. Canadian scientists Donald Jamieson, Moneca Price, and Vijay Parsa have established that digital mobile phones degrade the speech of people with atypical voices—including users of artificial larynges—adding another layer of communication disability. "Speech coders," they explain, "employ algorithms based on models derived from normal native-English talkers and from listeners with normal hearing."[109] While some elements of these speech and hearing models are indebted to the long history of voice modeling, coders now also incorporate statistical data derived from population sampling, a topic discussed in the publications of Jonathan Sterne and Adrian Mackenzie on audio and video codecs (increasingly complex and ubiquitous coder-decoder formats such as the MP3 and the MPEG-2).[110] In a milieu where "universal" and "normal" communication are conflated, the incompatibility between the telephone network (or at least some telephone handsets) and artificial larynges further constitutes the latter as a minor or marginal technology.

More broadly, commentators have questioned the relationship between electrical "communications" (i.e., technology) and everyday practices of human communication; do the infrastructure and ideals of the former modulate the latter? In 1939, Voder performances loosed anxieties about a future of robotic demagogues—mass control via engineered speech. The *Albuquerque Tribune* warned, "Voders—Frankenstein monsters equipped with vocal cords—geared to the precise speed and volume best calculated to induce mass hypnosis, will harangue humanity ceaselessly."[111] In his 1968 novel *The First Circle*, Aleksandr Solzhenitsyn instead condemned vocoding for its "dismemberment" of "normal" speech and its encouragement of simulation:

> Clipping, damping, amplitude compression, electronic differentiation and integration of normal human speech were engineering desecrations comparable to the dismemberment of a southern resort area like Novy Afon or Gurzuf into little fragments of matter, stuffing them into a billion match-boxes, mixing them all up, flying them to Nerchinsk, sorting them out and reassembling them in their new location so that the result could not be distinguished from the original—a re-creation of the subtropics, the sound of waves on the shore, the southern air and moonlight.[112]

Stalin, in the novel, has decided that "language is a tool of production." The academics and engineers imprisoned at a Moscow gulag are instructed, as was Solzhenitsyn during his own detention, to become the next "George Fletchers": to build a vocoder and a sound spectrograph for telephone encryption and surveillance. In his review of *The First Circle*, Raymond Williams queried the privileging of voice reproduction and identification over speech acts, over the work of "making common" done by communication: "This work on the human voice, on detecting it, is done by men who need also to speak, to describe their common condition."[113]

Some deaf authors, writing at the time of the vocoder's invention, more radically resisted the communication imperative as well as the ideals of vocal standardization and intelligibility promoted by techniques such as lip-reading. In her memoir *And No Birds Sing*, published in 1935, Pauline Leader describes losing her hearing as a teenager. Her mother refused to enroll her in a residential school where she might learn lip-reading; she also regularly hid her shoes and jacket to keep Leader from going outside. In the 1920s, at age seventeen, Leader ran away to New York, where she decided not to pursue sign language or lip-reading, finding them equally "ugly" and "obscene." She describes moving between her windowless rented room, a variety of manual jobs, and a lonely table at a Greenwich Village automat. She rarely has an exchange with anyone.

Leader eventually abandoned speech entirely, denaturalizing her voice by transforming her lips and larynx into a different sort of instrument:

> My voice was a wind. I played games with it. . . . When I talked I could feel through my fingers the melancholy sound the wind made. . . . I loved it. I talked, and as I talked, I would forget that I was talking and exactly what it was that I was saying, and listen to the wind, the monotonous wind, in my throat. Sometimes it was more the death-rattle of the wind than the swinging wind itself; again, the sound might be a series of little water-chuckles. Listening through my fingers, I would laugh at the sound, it was so happy. "Vibration," the people said with their usual lack of imagination. As in everything else, I preferred my own interpretation.[114]

Insisting on her "own interpretation," she refused the ideals of efficienty and universal communication and even the communicative function of speech. She listened more closely to "monotony" and heard something totally different than redundancy or impaired voice: laughter, a death-rattle, water-chuckles, and the free play of the "swinging wind itself."

Notes

1. An early, condensed version of this article was published in German as "Medien und Prothesen: Über den künstlichen Kehlkopf und den Vocoder," in *Klangmaschinen zwischen Experiment und Medientechnik*, ed. Daniel Gethmann (Bielefeld: Transcript Verlag, 2010), 129–54. Hereafter cited as "MP."
2. "Transcontinental Script for July 29, 1939," p. 2, Box 1061, 129-04-02-03, AT&T Archives.
3. "Pedro the Voder: A Machine That Talks," *Bell Laboratories Record* 17 (February 1939): 170.
4. AT&T Press Release (January 8, 1939), p. 3, Box 1061, 129-04-02-03, AT&T Archives. In the 1920s the Westinghouse Televox robot famously "spoke" using a sound-on-film loop. Scott Schaut, *Robots of Westinghouse: 1924–Today* (Mansfield, OH: Mansfield Memorial Museum, 2006).
5. T. W. Williams and L. N. Roberts, "Our Exhibits at Two Fairs," *Bell Telephone Quarterly* 19 (January 1940): 63.
6. "Voder Demonstration a Hit," *Long Lines*, March 1942, 7.

7. Vannevar Bush, "As We May Think," *Atlantic Monthly*, July 1945, http://www.theatlantic.com/doc/194507/bush/2.
8. Dave Tompkins has recently published the only full-length book on the vocoder, *How to Wreck a Nice Beach: The Vocoder from World War II to Hip-Hop* (New York: Melville House, 2010). Tompkins's love letter to the vocoder, widely researched, the book is unfortunately filled with factual and interpretive errors: mislabeled photographs and misattributed inventions, incorrect technical descriptions, and a conflation of the vocoder with other speech synthesizers and artificial talkers. Tompkins remixes a vast quantity of information on mechanical and electronic speech; the result is a provocative book that lacks social context and explanatory force.
9. For the first case see Friedrich Kittler, *Gramophone, Film, Typewriter*, trans. Geoffrey Winthrop-Young and Michael Wutz (Stanford: Stanford University Press, 1999), 111: "Funkspiel, VHF tank radio, vocoders, Magnetophones, submarine location technologies, air war radio beams, have released an abuse of army equipment that adapts ears and reaction speeds to World War n + 1. . . . Laurie Anderson's voice, distorted as usual on Big Science by a vocoder, simulates the voice of a 747 pilot who uses the plane's speaker system to suddenly interrupt the ongoing entertainment program and inform passengers of an imminent crash landing or some other calamity." For other examples see Jacob Smith, "Tearing Speech to Pieces: Voice Technologies of the 1940s," *MSMI* 2 (Autumn 2008): 183–206; Neal Stephenson, *Cryptonomicon* (New York: Eos, 1999).
10. Weheliye notes that "Hayles reinscribes white masculinity as the (human) point of origin from which to progress to a posthuman state." Alexander G. Weheliye, "'Feenin': Posthuman Voices in Contemporary Black Popular Music," *Social Text* 20 (Summer 2002): 23.
11. Manfred Schroeder, in discussion with the author, April 14, 2009. For more detail regarding the "voice-excited vocoder," "linear predictive coder," and "codebook excited linear prediction coder," see Manfred Schroeder, *Computer Speech: Recognition, Compression, Synthesis* (Berlin: Springer, 2004), 36–38. Hereafter cited as *CS*.
12. Lisa Scanlon, "Vocal Codes," *Technology Review*, November 2003, 80.
13. J. L. Flanagan, *Speech Analysis, Synthesis, and Perception* (Berlin: Springer-Verlag, 1965), 171, 244–45. Hereafter cited as *SASP*. Flanagan describes the "vocoder" as a "generic term" for any analysis-synthesis system.

14. Lloyd Espenschied, memorandum, "Re: Homer Dudley's Contributions of the Vocoder and Voder," January 25, 1949, p. 2, "Memos, Articles 1937–49 Dudley Vocoder–Synthetic Speech–Visible Speech" Folder, Lloyd Espenchied Collection, AT&T Archives.
15. "Redundant means superfluous, irrelevant means unnecessary. Superfluous information is information which exists several times in the data stream . . . or simply information which can be easily and losslessly recovered. . . . Irrelevant information is the type which cannot be perceived by the human senses." Walter Fischer, *Digital Television: A Practical Guide for Engineers* (Berlin: Springer, 2004), 65.
16. Lloyd Espenschied, "Various Suggestions for Speech Analysis and Synthesis Along the Lines of Mr. H. W. Dudley's Work—Case 37014," "Memos, Articles 1937–49 Dudley Vocoder–Synthetic Speech–Visible Speech" Folder, Espenchied Collection.
17. Dudley is not well known today, but his junior colleagues at Bell Laboratories saw him as part of a triumvirate that included Claude Shannon and William Shockley. Manfred Schroeder, "Homer W. Dudley Dies," Acoustics, Speech, and Signal Processing Newsletter, *IEEE* 52 (December 1980): 23.
18. Homer Dudley, "Synthesizing Speech," *Bell Laboratories Record* 15 (December 1936): 98–102. Hereafter cited as "SS."
19. Proposals for "harmonic" telegraphs in the 1870s suggested that multiple messages could be transmitted simultaneously down a single wire using "carrier" currents of different frequencies. Carrier multiplex systems were later adopted for voice telephony. E. H. Colpitts and O. B. Blackwell, "Carrier Current Telephony and Telegraphy," *Journal of the American Institute of Electrical Engineers* 40, no. 4 (1921): 205–300.
20. James Flanagan, "From the Doctoral Thesis Defense of C. Gunnar M. Fant," in *Frontiers of Speech Communication Research*, ed. Bjorn Lindblom and Sven Ohman (New York: Academic Press, 1979), 11.
21. Graham Pullin, *Design Meets Disability* (Cambridge: MIT Press, 2009), xiii.
22. See, for instance, the US Technology-Related Assistance for Individuals with Disabilites Act of 1988.
23. Richard Ladner, "Accessible Technology and Models of Disability," in *Design and Use of Assistive Technology: Social, Technical, Ethical, and Economic Challenges*, ed. Meeko Mitsuko K. Oishi, Ian M. Mitchell, and H. F. Machiel Van der Loos (New York: Springer, 2010), 25–33.

24. Katherine Ott, "The Sum of Its Parts: An Introduction to Modern Histories of Prosthetics," in *Artificial Parts, Practical Lives: Modern Histories of Prosthetics*, ed. Katherine Ott, David Serlin, and Stephen Mihm (New York: New York University Press, 2002), 21.
25. Henri-Jacques Stiker, *A History of Disability*, trans. William Sayers (Ann Arbor: University of Michigan Press, 2000), 128.
26. Gerard Goggin and Christopher Newell, "Introduction: The Intimate Relations between Technology and Disability," *Disability Studies Quarterly* 25, no. 2 (2005), http://dsq-sds.org/article/view/547/724.
27. Frank Jewett, "Electrical Communication: Past, Present, Future," *Bell Telephone Quarterly* 14 (July 1935): 172.
28. Frederik Nebeker, *Signal Processing: The Emergence of a Discipline, 1948 to 1998* (New Brunswick: IEEE History Center, 1998), 2–3. "Among the processes studied and devised by signal-processing engineers are filtering, coding, estimating, detecting, analyzing, recognizing, synthesizing, recording, and reproducing." In addition to economy, "improved transmission" meant accurately reconstructing a message despite noise or error during transmission. Nebeker notes that signal processing became a "discipline" in the second half of the twentieth century, although many of its principles were established earlier.
29. Lloyd Espenschied, "Report: Accomplishment of Homer Dudley in the Analysis and Synthesis of Speech" (April 6, 1949), p. 1, "Memos, Articles 1937–49 Dudley Vocoder–Synthetic Speech–Visible Speech" Folder, Espenchied Collection.
30. Lloyd Espenschied, "Homer Dudley's Development of Mechanized Speech in the so-called Vocoder and Voder" (March 29, 1949), p. 1, "Memos, Articles 1937–49 Dudley Vocoder–Synthetic Speech–Visible Speech" Folder, Espenchied Collection.
31. With similar insight in 1916, J. B. Flowers had used the transmitter of an Acousticon hearing aid, along with a galvanometer, to amplify and record whispered speech. By thus subtracting the action of the vocal cords, he hoped to determine "true nature of speech," which he then planned to apply to the construction of a voice-operated typewriter. This research was funded by Underwood. J. B. Flowers, "The True Nature of Speech," *AIEE Transactions* 35 (1916): 213–31.
32. Fuller taught at the Boston School for Deaf Mutes (later renamed the Horace Mann School), attended by Mabel Hubbard. After reading Visible Speech, she began using the Bell symbols to teach lip-reading. When Melville Bell came to Boston to give a Lowell Lecture in 1870,

she hosted him for an exhibit at her school. She later invited Alexander Graham Bell to train the teachers and pupils at the school in 1873. Her papers are part of the Alexander Graham Bell Association for the Deaf and Hard of Hearing Collection at the History Factory. For further details on the history of lip-reading, see Fred DeLand, *Story of Lip-reading: Its Genesis and Development* (Washington, DC: The Volta Bureau, 1931). Hereafter cited as *SLR*.

33. For instance, Juan Pablo Bonet's *The Method of Teaching Deaf Mutes to Speak* (1620) or John Bulwer's *Philocopus, or The Deaf and Dumbe Man's Friend* (1648).
34. For more complete histories of deaf education, see Harlan Lane, *When the Mind Hears: A History of the Deaf* (New York: Random House, 1984); Jonathan Rée, *I See a Voice: Deafness, Language, and the Senses—A Philosophical History* (New York: Metropolitan Books, 1999); Douglas Baynton, *Forbidden Signs: American Culture and the Campaign against Sign Language* (Chicago: University of Chicago Press, 1996).
35. Mabel Gardiner Bell, "The Subtle Art of Speech-Reading," *Atlantic Monthly*, February 1895, 170.
36. Lillie Eginton Warren, "Speech for Deaf Children," *Popular Science Monthly*, January 1894, 369.
37. John Durham Peters, *Speaking into the Air: A History of the Idea of Communication* (Chicago: University of Chicago Press, 2001), 31.
38. Régis Debray has argued that Norbert Wiener "as early as 1948 defined man without reference to interiority as a communication machine." Lip-reading, at least a half-century prior, anticipated this aspect of the cybernetic paradigm. Régis Debray, *Media Manifestos: On the Technological Transmission of Cultural Forms*, trans. Eric Rauth (New York: Verso, 1996), 54.
39. Brauckmann published a book on his method in 1925.
40. Elsewhere I have argued that the League, largely run by hard-of-hearing social workers, provides an early example of lay "activist expertise" in the medico-technical sphere. Mara Mills, "Deafening: Noise and the Engineering of Communication in the Telephone System," *Grey Room* 43 (Spring 2011): 118–43.
41. See, for instance, Notebook #7, 21150, p. 197, Homer Dudley Papers, AT&T Archives.
42. By the end of the decade nearly 60 percent of deaf people reported being able to read lips. The exact numbers were highest for those living in New England and the mid-Atlantic region, with white (presumably

well-off) females being most likely to lip-read. See Harry Best, *Deafness and the Deaf in the United States* (New York: MacMillan, 1943), 210–11. Best argued a strong correlation between lip-reading and the use of speech, as well as a steady rise in lip-reading in the first decades of the twentieth century.

43. "Deaf 'Hear' Two Miles in Television Test," *New York Times*, July 3, 1930, 15.
44. Edward B. Nitchie, "The Eye as a Substitute for Deaf Ears," in *New Lessons in Lip Reading*, ed. Elizabeth Helm Nitchie, 2nd ed. (Philadelphia: Lippincott, 1940), 25.
45. Edward B. Nitchie, "To the Friends of the Deaf," in *New Lessons in Lip Reading*, ed. Elizabeth Helm Nitchie, 2nd ed. (Philadelphia: Lippincott, 1940), 23.
46. Frances Warfield, *Keep Listening* (New York: Viking Press, 1957), 33.
47. Persis Vose, "Lip Reading and Algy," in *Say It Again* (Portland, ME: Southworth Press, 1931), 11. Similarly, Marie Hays Heiner imagined that using either lip-reading or sign language would mean that she was "going to be a 'handicapped.'" Marie Hays Heiner, *Hearing Is Believing* (Cleveland: World Publishing Company, 1949), 17.
48. J. C. Furnas, "My First Ten Years with a Hearing Aid," *Saturday Evening Post*, June 1, 1957, 40.
49. Earnest Elmo Calkins, "And Hearing Not—," *Annals of an Adman* (New York: Scribner, 1946), 189.
50. Grace Barstow Murphy, *Your Deafness Is Not You* (New York: Harper and Brothers, 1954), 147.
51. Albert Ballin, *The Deaf Mute Howls* (Washington, DC: Gallaudet UP, 1998), 28.
52. Homer Dudley, "Fundamentals of Speech Synthesis," *Journal of the Audio Engineering Society* 3 (October 1955): 172.
53. Writing in 1999, however, Schroeder admitted, "It is still difficult to extract these parameters from a running speech signal." Manfred Schroeder, "Speech Processing," in *Signal Processing for Multimedia*, ed. Jim Byrnes (Amsterdam: IOS Press, 1999), 129.
54. Homer Dudley, "The Carrier Nature of Speech," *Bell System Technical Journal* 19, no. 4 (1940): 496.
55. Homer Dudley, "The Automatic Synthesis of Speech," *Proceedings of the National Academy of Sciences of the USA* 25, no. 7 (1939): 378. Hereafter cited as "AS." John Pierce explains that the process works "as though we had taken a human subject and, using advanced medical techniques, separated him from his vocal tract, removing it to a

distant point while at the same time preserving the nerve connections which control the tract by elongating them into a cable. In order to transmit speech, we talk to this person, and he listens and repeats our words with the proper inflection, stress patterns and pronunciations to the listener at the receiver." John Pierce, *Man's World of Sound* (New York: Doubleday, 1958), 250.

56. Dudley acknowledged that his first model was a very loose approximation of the ear, with the frequency bands chosen through trial and error. Dudley's "channel vocoder" was followed by a "formant vocoder," developed by James Flanagan.
57. Jonathan Sterne, *The Audible Past: Cultural Origins of Sound Reproduction* (Durham: Duke University Press, 2003), 80.
58. Marshall McLuhan, *Understanding Media: The Extensions of Man* (1964; Cambridge: MIT Press, 1994), 44–45.
59. Hal Foster, *Prosthetic Gods* (Cambridge: MIT Press, 2004), 109. Foster perceives a false opposition between "the machine" and "the body" as underlying this double logic.
60. See Bernard Stiegler, *Technics and Time, 1: The Fault of Epimetheus* (Stanford: Stanford University Press, 1998).
61. Vivian Sobchack, "A Leg to Stand On: Prosthetics, Metaphor, and Materiality," in *The Prosthetic Impulse: From a Posthuman Present to a Biocultural Future*, ed. Marquard Smith and Joanne Morra (Cambridge: MIT Press, 2006), 17–41. Related critiques have been made of bionics, cyborgs, and posthumans. See, for example, Tobin Siebers, "Disability in Theory: From Social Constructionism to the New Realism of the Body," in *The Disability Studies Reader*, ed. Lennard J. Davis (New York: Routledge, 2006), 173–83.
62. On the other hand, there is the danger of reading "prosthesis" as only normalizing for some, and always extending for others. Sarah Jain, "The Prosthetic Imagination: Enabling and Disabling the Prosthesis Trope," *Science, Technology, & Human Values* 24 (Winter 1999): 31–54.
63. Marquard Smith and Joanne Morra, eds., *The Prosthetic Impulse: From a Posthuman Present to a Biocultural Future* (Cambridge: MIT Press, 2006), 1–2.
64. *Speech Pathology*, a 1931 textbook by Lee Edward Travis of the University of Iowa, was one of his sources. Godfrey Dewey's *Relative Frequency of English Speech Sounds* was another. Laboratory Notebook 1, 1924–1934, p. 162, Dudley Papers, AT&T Archives.
65. Homer Dudley and T. H. Tarnoczy, "The Speaking Machine of Wolfgang von Kempelen," *Journal of the Acoustical Society of America*

22 (March 1950): 151–66. See also H. Dudley, "The Automatic Synthesis of Speech," *Proc. NAS of the USA* 25, no. 7 (1939): 377–83; Homer Dudley, R. R. Riesz, and S. S. A. Watkins, "A Synthetic Speaker," *Journal of the Franklin Institute* 227 (June 1939): 739–64.

66. "The first speaking 'chip' was not etched in silicon but carved out of wood" (*CS* 25).
67. In "MP" I trace von Kempelen's influence from Wheatstone to Bell to AT&T. See also Thomas Hankins and Robert Silverman, "*Vox Mechanica*: The History of Speaking Machines," a chapter that covers the proposals and devices of John Wilkins, Abbé Mical, Georges Marage, and others. Thomas Hankins and Robert Silverman, *Instruments and the Imagination* (Princeton: Princeton University Press, 1995), 178–220.
68. "An Electronic Artificial Larynx," *Bell Laboratories Record* 38 (October 1960): 363; "Artificial Larynx 1935–1939, Book I," 170-10-02, Folder 20836, AT&T Archives.
69. "An Artificial Larynx: A Second Attempt at a Most Delicate Surgical Operation," *New York Times*, February 26, 1887, 3.
70. Indeed, even in 1936, AT&T only sold ninety artificial larynges to men and five to women, and in 1937 they sold seventy-seven and two, respectively. J. O. Perrine, "The Artificial Larynx," Memo, November 17, 1938. AT&T Archives.
71. Within disability studies, as in the language of the 1990 Americans with Disabilities Act, "impairment" usually designates a physical or medical condition, while "disability" designates the social responses to, or social construction of, that difference.
72. W. L. Hanson, "A New Artificial Larynx with a Historical Review," *Illinois Medical Journal* 78 (December 1940): 484. Hereafter cited as "NALHR."
73. Dr. Johannes Horowitz, "Discontent in Austria," *New York Times*, August 20, 1899, 15.
74. Samuel Iglauer, "Artificial Larynx with Patient Demonstrating Its Use," *Annals of Otology, Rhinology and Laryngology* 45 (1936): 1176–77. Others learned esophageal speech and similar "pseudovoices."
75. Alexander Graham Bell, *The Mechanism of Speech* (New York: Funk & Wagnalls, 1907), 8. David Foulis mentions an 1877 exhibition of his patient to Bell and others in "Extirpation of the Larynx," *The Lancet*, January 26, 1878, 118–20.
76. Yvan Lebrun, *The Artificial Larynx* (Amsterdam: Swets & Zeitlinger, 1973), 45–46. Hereafter cited as *AL*.

77. Paul Holinger, “A Century of Progress of Laryngectomies in the Northern Hemisphere,” *Laryngoscope* 85 (February 1975): 325.
78. “Western Electric Supplies Dumb with Voices,” *Western Electric News* 14 (January 1925): 30.
79. J. E. Mackenty, “The Operative Treatment of Cancer of the Larynx,” *Journal of Laryngology and Otology* 39 (February 1924): 77.
80. John Edmund Mackenty, *Cancer of the Larynx* (New York: American Medical Association, 1927), 58.
81. This number rose to fifteen hundred by 1931. Mr. Bancroft Gherardi to Mr. H. P. Charlesworth, August 26, 1931, 119-03-01-03, AT&T Corporate Collection, AT&T Archives.
82. R. R. Riesz to C. T. A. McCormick, March 16, 1931, Filecase 20446, 417-04-02-14, “Volume A—Development of an Artificial Larynx,” AT&T Archives.
83. Colonel Charles Burt to R. R. Riesz, March 27, 1931, Filecase 20446, 417-04-02-14, “Volume A—Development of an Artificial Larynx,” AT&T Archives.
84. Miss Grace C. H. to R. R. Riesz, March 27, 1931, Filecase 20446, 417-04-02-14, “Volume A—Development of an Artificial Larynx,” AT&T Archives.
85. Later, the 2-B offered a higher fundamental frequency for female users.
86. Letter from G. W. O., March 2, 1936, 170-10-02, Folder 20836, Book I, AT&T Corporate Collection.
87. Dr. Lynch to G. F. Fowler, July 17, 1935, 170-10-02, Folder 20836, Book I, AT&T Corporate Collection.
88. R. R. Riesz, “Description and Demonstration of an Artificial Larynx,” *Journal of the Acoustical Society of America* 1 (January 1930): 273–79. See also R. R. Riesz, “Restoring Speech with the Artificial Larynx,” *Bell Laboratories Record* 8 (October 1929): 1–3.
89. Stephen Fletcher, Vice President of Western Electric, quoted in Edmund Prince Fowler, “Historical Vignette: Harvey Fletcher,” *Archives of Otolaryngology* 86 (January 1967): 109.
90. Lebrun has detailed this phonography experiment: “An electric prosthesis comprising a phonograph of the Edison type driven by an electromotor and connected with a receiver that was fitted into the patient’s nose or attached to his denture. On the cylinder of the phonograph a vowel, i.e. a succession of damped oscillations, produced by a singer had been recorded. When the recording was played back, each damped oscillation in the record originated an electric current that energized the membrane of the receiver. The movement to and

fro of the membrane caused the air in the buccal cavity to vibrate: vocal waves arose that retained most of the qualities of the singer's voice but owed their timbre to the configuration of the patient's vocal tract at that moment . . . this kind of artificial voice production Gluck aptly called 'eine Stimmkonserve.'" *AL*, 56.

91. For his influential article see J. Q. Stewart, "An Electrical Analogue of the Vocal Organs," *Nature* 110, no. 2757 (1922): 311–12. Hereafter cited as "EAVO."
92. Richard Paget claimed to have arrived at the same theory, independent of Stewart. Richard Paget, *Human Speech* (New York: Harcourt, Brace, 1930), 74. And, in 1924, Fletcher electrically synthesized the words "mama" and "papa" during a presentation for the New York Electrical Society.
93. R. W. Wegel, "Theory of Vibration of the Larynx," *Bell System Technical Journal* 9 (1930): 207.
94. In 1931, Riesz produced a larynx with an electrical source of sound. This was lent to Senator Coleman DuPont, on whom Mackenty had performed a laryngectomy, but he "made little use of it" because the tone and loudness were unsatisfactory. R. R. Riesz to C. T. A. McCormick, March 16, 1931, Filecase 20446, 417-04-02-14, "Volume A—Development of an Artificial Larynx," AT&T Archives. AT&T finally developed an electronic larynx, which superseded the mechanical version, in 1960.
95. Later, Dudley also cited the vowel synthesizer built by Karl Willy Wagner, director of the Heinrich-Hertz-Institut in Berlin, which used four different electrical resonators. K. W. Wagner, "Ein neues elektrisches Sprechgerät zur Nachbildung der menschlichen Vokale," *Abhandlungen der Preussischen Akademie der Wissenschaften* 2 (Berlin, 1936).
96. The pitch band of the analyzer determined the pitch of this buzz.
97. Homer Dudley, "Remaking Speech," *Journal of the Acoustical Society of America* 11, no. 2 (1939): 169.
98. The *New York Times* announced, "It was the first time in history an artificial larynx had spoken to a plane in the air." "Plane Gets Message by Artificial Voice," *New York Times*, October 24, 1929, 8.
99. "'Soundless Sound' 'Heard' by Brain," *New York Times*, November 21, 1930, 25.
100. Captain Ingraham to J. S. Cantlen, November 17, 1944, 170-10-02, Folder 20837, Book II, AT&T Corporate Collection. Hereafter cited as "CI."
101. Ingraham regularly tinkered with his device, reporting, "The in-

creased length of the mouthpiece has, I believe, the effect of lowering the pitch of the larynx. However, even with the short mouthpiece originally furnished, the pitch presently is much too low . . . to raise the pitch to that of my former natural voice, it is necessary to add the dampener unless there is some other method about which I am not informed. When I do so, I lose inflection" ("CI").

102. Moreover, the early vocoder did not work equally well for all speakers, having particular trouble with feminine voices. Homer Dudley, Laboratory Notebook 6 (#19687), p. 94, January 8, 1945, AT&T Archives.

103. Homer Dudley, "The Vocoder," *Bell Laboratories Record* 18 (December 1939): 126. Physicist and screenwriter Gilbert Wright patented his Sonovox based on principles similar to those of the vocoder (which he discovered while shaving with an electric razor and changing the shape of his open mouth). He marketed the Sonovox to the film industry as a tool for sound effects; an initial "ghost voice" demo (which he made using a phonograph record of blustery wind) was deemed "too scary" for American audiences, but the Sonovox eventually became the technique for the talking train in *Dumbo* (among many other things). In 1943, Aurex Corporation adapted the Sonovox as an artificial larynx—in this case, using a simple and much more limited harmonic sound source.

104. Andrew Hodges, *Alan Turing: The Enigma* (New York: Simon & Schuster, 1983).

105. David Robertson, "The Radical Who Shaped the Future," *IEEE Review* 48 (May 2002): 31–32. Hereafter cited as "RWSF."

106. As Robertson notes, PCM would only become a commercial success after transistorization ("RWSF").

107. Schroeder argues that Dudley's vocoder incorporated some elements of perceptual coding, which is now the basis for the MP3 format. "Even some dark-age speech coders, like the channel vocoder, incorporate properties of human hearing: the channel vocoder preserves only the amplitude spectrum of speech sounds and discards the phases" (*CS*, 126).

108. John Mills, "Electrical Communication," *Scientific Monthly*, August 1945, 139.

109. Donald G. Jamieson, Vijay Parsa, and Moneca C. Price, "Interaction of Speech Coders and Atypical Speech I: Effects on Speech Intelligibility," *Journal of Speech, Language and Hearing Research* 45 (June 2002): 483. See also part 2 in the August issue.

110. Jonathan Sterne, *MP3: The Meaning of a Format* (Durham: Duke University Press, 2012); Adrian Mackenzie, "Codecs," in *Software Studies: A Lexicon*, ed. Matthew Fuller (Cambridge: MIT Press, 2008), 48–54.
111. "Beware of Voder!" *Albequerque Tribune*, January 7, 1939. Copy held in "Clippings" folder, Dudley Papers, MIT Archives.
112. Aleksandr Solzhenitsyn, *The First Circle*, trans. Thomas P. Whitney (1968; Evanston: Northwestern University Press, 1997), 50.
113. Raymond Williams, "Work on the Human Voice," *The Guardian*, December 18, 1968, http://books.guardian.co.uk/departments/classics/story/0,,106492,00.html.
114. Pauline Leader, *And No Birds Sing* (New York: Vanguard Press, 1931), 131.