Potential Energy and the Body Electric: Cardiac Waves, Brain Waves, and the Making of Quantities into Qualities
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Potential Energy and the Body Electric

Cardiac Waves, Brain Waves, and the Making of Quantities into Qualities

by Stefan Helmreich

Physics tells us that potential energy is the capacity to do work that a body possesses as a result of its position in electric, magnetic, or gravitational fields. Thinking of "potentiality" in an electric idiom and with reference to its place in human biological processes that implicate electric phenomena, such as the pulses of action potentials that animate the heart and brain, can afford novel angles into contemporary biomedical enactments of humanness. This paper explores the material and rhetorical power of electric potential in cardiac and neurological medicine, paying attention to how discourses of "waves" of energy format the way scientists apprehend bodies as emplaced in time—in a time that can be about both cyclicity and futurity. Attention to electrophysiological phenomena may enrich the way anthropologists of the biosciences think about potentiality, taking scholars beyond our established attentions to the genetic, cellular, or pharmacological to think about the body electric.

How do human hearts keep beating? The biomedical account tells us that specialized cells called "pacemakers" discharge electrical impulses that travel as propagating waves through the walls of the heart, prompting the heart muscle to contract. The heart muscle, a webwork of long wiggly cells, is an "excitable medium," a substrate in which wave action does not attenuate over time (as with, say, sound propagation in air) but is rather continually renewed (by, in this case, cellular relay). The heartbeat is inaugurated by an "action potential," a rapid surge of electrical activity as heart cells quickly change the voltage difference between the insides and outsides of their membranes (Barnett and Larkman 2007). Such surges have, since the early twentieth century, been mapped and monitored using electrocardiograms (EKGs), inscriptions that graph as wave forms changes over time in the heart's electric potential (fig. 1). The heart's action potential is not about grand human futures and possibilities but about small, cyclically recurring prompts, futures that pass quickly—from one second to the next for a normal heart—into the past. Attention to such electrophysiological phenomena—and to the practices and descriptions that render them knowable and visible—may enrich the way anthropologists of the biosciences think about potentiality, taking scholars beyond our established attentions to the genetic, cellular, or pharmacological. What I offer here are not so much "postgenomic" anthropological reflections as they are thoughts about a body parallel to those conjured by molecular biology, tissue culture, and reproductive technology: a body electric.[1]

Recent anthropological consideration of the concept of potentiality has been bundled with attention to how people grappling with biomedical and biotechnological promise and peril act on and speculate about "the future" (e.g., Fortun 2008; Franklin 2006; Kaufman et al. 2010; Samimian-Darash 2009; Svendsen 2011; Thompson 2005). As the introduction to this special issue of *Current Anthropology* suggests, claims about "potential" often point both to putatively "natural," possibly teleological, forces considered to be latent within organisms as well as to those possibilities that might be socially realized as people select how to direct such forces in the near and not so near term.

But potentiality is also at work in the ongoing present, as a persistent operator at smaller timescales and in iterative, repetitive processes such as heartbeats—or, as I will also discuss below, in the propagation of impulses through the brain. Potential thus operates not only in such vanguard biomedical practices as genomics and bioinformatics but also in more everyday, routinized protocols such as those that create the mundane artifacts of EKGs and electroencephalograms

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1. Of course, genomic and electric bodies are never separate; even the apotheosis of molecular biological practice, the high-profile cloning of Dolly the lamb in 1997 by embryologist Ian Wilmut, saw the use of an electric current to fuse egg and cell in the processes of somatic cell nuclear transfer. Right now, with the neurosciences garnering growing scientific and popular attention (for anthropological analyses, see Dumit 2004; Langlitz 2013; Rees 2010; Schüll and Zaloom 2011), one might argue that the electrically circuited, networked body is moving into new visibility (see also Heinemann and Heinemann 2010; Martin 2013).

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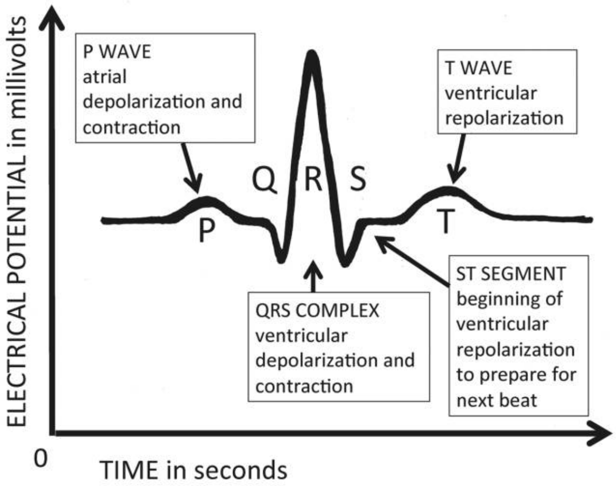

Figure 1. Schematic of an electrocardiographic tracing of a single cardiac cycle (from one heartbeat to the next), with waveforms labeled. Redrawn and adapted from http://hyperphysics.phy-astr.gsu.edu/hbase/biology/ecg.html, and http://www.meditech.cn/meditech-edu/ecg-1.asp.

(EEGs; see Hacking 2006, which calls for renewed attention in social studies of biomedicine to quotidian technological objects). Electrophysiological accounts can tune us into new ways of making connections between very small-scale presents and long-term promissory futures.

Physics defines potential energy as the capacity to do work that a body possesses not as a function of its ongoing motion but as a function of its position in electric, magnetic, or gravitational fields. The term "potential energy" was coined in 1853 by Scottish engineer William Rankine (who contrasted it with "actual energy"), and potential energy was theorized further by physicist William Thompson (aka Lord Kelvin), who contrasted it with "kinetic energy." Potential energy was conceived as a mechanistic force operating in a world composed of continuous fields of matter; it was woven into the fabric of the thermodynamic account of the universe that in the mid-nineteenth century replaced Cartesian visions of the cosmos as a vast void dotted only here and there by matter (Smith 1999; Smith and Wise 1989).[2] Potential energy was what Rankine sometimes called "latent energy"—stored energy that only awaited release. For William Thompson's engineer brother, James, potential energy was manifestly at work in human bodies: "It seems to me," he wrote in an 1862 letter to William, "a perfectly admissible supposition that mind or vitality may have the power, in the living body, of collecting, and applying as potential energy, the energy . . . stored indefinitely everywhere as heat" (quoted in Smith and Wise 1989:620). Potential energy animated people—particularly, as electrophysiologists would later have it, through the constant rising and falling of clumps of "action potentials."[3]

In this essay, I am interested in how potential energy—stored and released in electrically mediated, often periodic processes in bodies—is described and manipulated in biomedical practice and discourse. Exploring the push and pull of potentialities, I pay particular attention to how dynamics and models of "waves" of energy format the way scientists apprehend bodies and bodily processes as emplaced in time. I draw on anthropological, sociological, and historical works about cardiac and neural monitoring to track these themes. Placing electromagnetic waves of potential at the heart of my analysis offers not only something of a nongenomic take on biology but also opens up the body (electric) to new kinds of contexts—contexts, for example, of electromagnetic pollution that might interfere with cardiac and neural functions and futures. In an age when more and more technologies exist in a web of wireless signals, taking notice of how our electromagnetic bodies also sit in these fields of power can pay political and analytic dividends.

I zero in on waves associated with two organs that are key symbols and substances of life: the heart and the brain. Both are defining organs for thinking about life and its difference from death, and both have been imaged as the seat of governance for the body. I describe how cardiac and brain waves have become technical objects through their partial inscription as traces on EKGs and EEGs. These objectifications are so commonplace as often to go unremarked; the EKG is a popular sign of ongoing (or attenuating) life process in everything from television shows to cartoons. I offer a few examples of how these objectifications in the medical context have become instruments for monitoring and for interventions that aim to transform cellular electric potential into biographical, human life potential. This transit—leaping across scales (from the cellular to the biographical) as well as symbolic registers (from science to sentiment)—is bound up with projects that seek to leverage technologies of quantity into realizations of quality. Properly quantified (and quantized) action potentials are, in the practices I describe, cor-

2. This fund of potentiality comes free, as it were, with being embodied. Indeed, potentiality comes with the universe. According to Crosbie Smith and Norton Wise (1989), William Thompson's vision of the universe as made of energy that might move between potential and kinetic states was ultimately grounded in "his theology of nature in which God had created energy *ex nihilo* in the beginning by His absolute power and had sustained its quantity by His ordained power. . . . Potential energy [was] . . . the original form of energy" (533).

3. What are now called "action potentials" were first called "negative oscillations" ("negative Schwankung") in 1872 by Emil du Bois-Reymond (see Finkelstein 2003). Julius Bernstein, a student of du Bois-Reymond (as well as of Helmholtz), in 1902 proposed an early theory of how these pulses worked (Schuetze 1983). In the late 1930s, Alan Lloyd Hodgkin and Andrew Huxley used the giant axon of the Atlantic squid to demonstrate how ionic currents propagated through neurons, work that delivered the now canonical model of action potentials, for which Hodgkin and Huxley won a 1963 Nobel Prize. On a deeper history of electrophysiology going back to eighteenth-century debates between Galvani and Volta on "animal electricity," look to Pera (1992). See also Lenoir (1982) on Hermann von Helmholtz's nineteenth-century research on nerve impulses.

ralled to add up to (it is hoped) better quality of life (though see Martin 1999). However, these periodic waves sometimes suffer interference when their potentials are detoured in unexpected directions, as with, say, electrical interference with cardiac monitoring systems or with neurological function—to say nothing of the force fields of race, class, gender, and nation that contour whose waves get monitored when, how, and for what.

An orienting note: waves are tricky to think about. Waves are not merely material processes of energy propagation or of vibration. They are also abstractions crafted by scientists who decide what will count as wave activity, whether in a passive medium (as with water waves, sound waves), an excitable medium (as with cardiac and brain waves), or in a vacuum (as with light waves or radio waves; Barad 2007). Literary critic Gillian Beer (1996) has examined the popular reception of wave theory in physics alongside early twentieth-century modernism, noting that both emphasized the transitory and illusory character of the apparently solid world (Beer points readers to the etheric ocean of wireless radio and to Virginia Woolf's novel of fluid subjectivities *The Waves*). Beer suggests that the electromagnetic "wave" enters the modernist world as a token of a self-conscious relativism about representational schemes. This doubleness is still with us today. Waves are at once processes as well as traces of those processes—traces inscribed in graphs or charts and, less obviously, in the very model of waves that is bound up with their observation. Waves are manifestations of the release of potentiality as well as signs of its continued efficacy. They serve here as vehicles for thinking about the relation between presents and futures of potential, realized and otherwise.

Heart

Étienne-Jules Marey, the nineteenth-century French inventor of cinematographic techniques for capturing periodic phenomena—his snapshots of horses running, which reveal the dynamics of their gaits, are emblematic—conducted early work on the activity of the heart. His 1857 dissertation reported on work with a kymograph (a revolving cylinder), which permitted him to inscribe on paper sequences of wavy lines that were created by arterial pulsation (Kroker 2007:93). His work sought graphically to register the sequence of relaxation and contraction in the heart—the cardiac cycle—and offered a visual representation of physiological temporality that other researchers had historically accessed primarily via touch—feeling for a pulse—or through sound—listening through stethoscopes.

Stethoscopes, Marey and others worried, could not always cleanly resolve distinct cardiac processes, which often very quickly succeeded one another in time. Marey sought what Lorraine Daston and Peter Galison (2007) have called "mechanical objectivity," seeking to sidestep subjective judgment, which was then associated with the uncertainty of sound as a source of reliable information (see Sterne 2003 on sound and early mediate auscultation, Schwartz 2011 on the idiosyncratic practice of simile involved in naming heart sounds, and Rice 2011 on today's stethoscopy).[4] He was concerned to banish vitalism from medicine and thought that graphical devices, such as those used in the physical sciences, could exile superstitious beliefs in an élan vital: "Inscribing instruments are to be found everywhere," Marey wrote, "in the observatories of astronomers and meteorologists, in physics laboratories, and in those of physiology" (quoted in Kroker 2007:94). Though Marey was recording physical motions and not electricity, his graphs are sometimes described as ancestors of today's EKGs (Lüderitz 2009; Snellen 1980), precursors to charts of the heart as an electric object rather than as primarily or only a hydraulic entity.[5]

EKGs are graphical traces of heart activity, particularly the waves of depolarization and repolarization that travel through heart muscle as cells change their electrical charges with the contraction and relaxation of the heart.[6] Looking at figure 1, in which the *X*-axis is time and the *Y*-axis is electrical potential difference (or voltage) between two leads attached to the body, one sees an ideal/typical wave tracing. Two-dimensional tracings of P waves (depolarization) and T waves (repolarization) in EKGs are partial representations, inscriptions, of three-dimensional waves reconstructed from data delivered by electrodes attached to bodies. An EKG can be read as a representation of changes over time in the electric potential in the heart.

In *Broken Hearts*, historian of medicine David Jones discusses how cardiologists have employed these tracings:

> Cardiologists, interested in diagnosing living hearts, learned to use electrocardiograms to classify the severity of the damage during or after a heart attack. When they interpreted EKGs, they distinguished several phases of the tracing. These corresponded to different parts of the cardiac cycle: the atria contracted, filling the ventricles with blood (the P wave); the ventricles contracted, pumping blood through the body (the QRS complex); and the ventricles repolarized in preparation for the next beat (the ST segment). Instead of simply diagnosing a heart attack or a myocardial infarction, cardiologists in the 1970s specified whether the patient had ST segment elevations (an early sign of myocardial ischemia and hypoxia) or pathological Q waves (a sign that part of the ventricle wall had infarcted and become a scar). They

4. The history of medicine would later see the graphic and the sonic fused to deliver composite, layered accounts.

5. A view of the heart as electric was in place by 1887, when the first EKG was created by physiologist Augustus Desiré Waller in London (see Lüderitz 2009).

6. Electrocardiograms are known in the United States as EKGs more frequently than ECGs, preferred in the United Kingdom. The *K* retains and refers to the German *kardio.*

> also learned to correlate these classifications with those used by pathologists. Patients with Q waves and ST segment elevation almost always had transmural infarctions. (Jones 2013:59)

Waves of activity in the heart, mapped onto inscriptions of graphical waves (often called "wave forms"), have become technical objects, useful in diagnosis and in planning courses of medical treatment whether by drugs or surgery.

More recently, EKGs have also enabled novel sorts of monitoring and management, near and remote. Take, for example, the internal cardiac defibrillator (sometimes "implantable cardioverter defibrillator"), or ICD, a device implanted into heart failure patients that monitors heart rate, uses an algorithm to detect possible arrhythmias, and can administer small shocks to jolt the heart back on track, beating with appropriate regularity and tempo (see Dickerson 2002; Grew 2011; Jeffrey 2001; Kaufman et al. 2011; Pollock 2008). Where a pacemaker imposes its periodicity on the heart, ICDs are meant to reset the heart to restore a healthy spontaneous rhythm. ICDs are technologies of intervention, with the promise/threat of (it is hoped) salutary shocks. The network of the heart's action potentials, should they go awry (as a result of arrhythmias of various sorts, some to do with heart diseases, some not), is shocked into disciplined waviness by this machine, which is constantly generating EKGs. The ICD's careful monitoring and administration of the second-to-second potentials coursing through cardiac muscle is meant to keep those potentials coming—to delay the eventual decline of the heart, an organ that science studies scholar Anne Pollock (2010) identifies as "intrinsically doomed" (the heartbeat, after all, is a sign of life and death both). Electric potential as immanent force is modulated into a recipient's life potential, quantity into quality.[7] Two meanings of potential come into focus here: potential as organic latent force and potential as a culturally channeled capacity.

In her ethnography of ICD recipients, Pollock (2008) shows that people with ICDs often experience the transformative logic of the device somewhat differently (Grew 2011). Each shock from an ICD is not just a promise of potential life but also works as a reminder of potential death. What if the shock does not work? What if the machine keeps trying to right the heart but never succeeds, leading to a particularly unpleasant death, a mix of low-level electrocution followed by myocardial infarction? "I don't know if I'm going to get shocked nine times before I die," worries one of Pollock's (2008:102) informants. And what if the machine malfunctions? According to some professionals, earlier models of ICDs actually ran the risk of prompting rather than preventing dangerous cardiac events. In their article "The Proarrhythmic Potential of Implantable Cardioverter-Defibrillators," cardiologist Sergio Pinski and his colleague Gerard J. Fahy (1995) warn that "the implantable cardioverter-defibrillator (ICD) is remarkably effective in preventing sudden cardiac death in high-risk patients, but it also has the capacity to provoke or worsen cardiac arrhythmias" (1651). The use of prompts for action potentials, aimed at extending potential life, can harbor potential uncertainty. On the other hand, what if the machine functions as it should? Pollock reports that the fear of potential shock looms large for many recipients, causing them to curtail physical activities they suspect (though never know) may lead to an electric jolt. Electric potential—cellular and machinic—is changed into a hovering threat. We might say that a cardiac/ICD "action potential" inhibits the patient's own "action potential" at another scale.

Medical anthropologist Sharon Kaufman and her colleagues (Kaufman et al. 2011; cf. Dickerson 2002), in their ethnographic study of ICD implantees age 80 and above, suggest that ICDs may not only prolong the state of "dying of heart failure" but may also permit people to die of other, perhaps less desirable causes. In this way, Kaufman et al. argue, the ICD is an "ironic technology"; as a means to an end (preventing possible death now), it may produce other ends (e.g., worse or other deaths later; Kaufman et al. 2011:11). All these dynamics are crosscut by radical inequalities in health care, especially in the United States; in 2007, the *Journal of the American Medical Association* reported that "black women were 44% less likely to get an ICD than were white men; white women were 38% less likely to get an ICD than white men, and black men were 27% less likely to get an ICD than white men."[8] Minute-to-minute action potentials sit not just within electric fields but also within racial and gender formations.

The newest ICDs come with wireless connections. These permit the downloading of data to a portable transmitter, which can then relay data to physicians, making it possible to monitor a person's cardiac processes remotely. A recent technological review article summarizes what happens next:

> Data are then sent to a central database using either the analogue landline phone system and a toll-free number (Boston Scientific, Medtronic and St-Jude Medical systems) or via the GSM network (Biotronik). The data are processed and made accessible to the physician on a secured webpage.

7. This is assuming that a regular heartbeat is itself a sign of health. Emily Martin (1999) reports that cardiology researcher Ary Goldberger and his colleagues have suggested that "the heart and other physiological systems may behave most erratically when they are young and healthy. Counterintuitively, increasingly regular behavior sometimes accompanies aging and disease. Irregularity and unpredictability, then, are important features of health" (quoted in Martin 1999:104; Goldberger is now Harvard Medical School Professor of Medicine, where he researches fractal patterns in ECGs. His tutorial for students is found at http://ecg.bidmc.harvard.edu/maven/mavenmain.asp).

8. "This is true even when the researchers compared people with the same medical conditions, the same age, and the same insurance coverage"; Daniel J. DeNoon for WebMD, http://www.webmd.com/heart-disease/news/20071002/icd-gap-for-women-and-african-americans (accessed November 2, 2012). A properly ethnographic project about ICDs would look closely at demographic and individual differences in how these devices are experienced.

> The physician is informed by e-mail, SMS, fax, or phone messages whenever critical data are available for consultation. The types of events which trigger an alert can be customized for each patient. (Burri and Senouf 2009:702)

A thick chain of transduction operates here, one that involves particular companies' devices, a variety of landline and cellular telephone plans and networks, and a host of medical data processing sites (to say nothing of the layered history behind ICDs, tested first in dogs in the late 1960s).[9] The literature makes clear that it is not usually a specific physician who looks over ICD data sent to a medical facility but rather teams of specialized technicians who scan data on a website that has been arranged to bring the most concerning cardiac profiles to the top (Burri and Senouf [2009] call this "data triage"; see Varma et al. 2010 for sample web pages). Such practices represent the routinization and internetification of what David Armstrong (1995) called "surveillance medicine."

At present, medical professionals do not send signals back to an ICD but rather place a phone call to patients telling them either not to worry or to come in for examination. Two-way communication via wireless ICD is a technical possibility; it is a social choice not to pursue it. The remote and human administration of shocks is (apparently) not yet something with which people are comfortable. There have also been warnings about the possibility of ill-intentioned people hacking into other people's ICDs and administering shocks (see Halperin et al. 2008).

More likely as a source of interference is interference. As with any electromagnetic process, interference is always a possibility. In the best circumstance, ICDs intervene only as necessary to keep the heart's action potentials working steadily, ensuring more potential life for the persons into whom they are implanted. But ICDs are electrical devices and exist in a media-ecological relation with other devices. ICD websites list electronic devices that may interfere with proper ICD function, such as cell phones, sonic toothbrushes, lawn mowers, and slot machines (see http://www.medtronic.cz/wcm/groups/.../electromagnetic-compatibility.pdf). Headphones are a particular worry (Lee et al. 2009). ICDs may also detect ambient electrical noise that prompts them to administer shocks; the *Journal of Invasive Cardiology* reports one instance in which a 70-year-old man "experienced [his] first ICD shock without any warning symptoms after switching the bathroom lights on at his vacation home" (Paraskevaidis, Polymeropoulos, and Louridas 2004:339). The particulars of the case are instructive: the man was using an ICD manufactured in the United States inside his vacation home in Greece, where everyday voltage (electric potential difference) is much higher. The potentials of technology sit inside worlds of energy conditioned by social, political, economic, national, and institutional forms of life.

Waves of energy in the heart, mapped as waves on EKGs inside ICDs, become resources for self-correction, for keeping potentiality in line—so long as electric potentials from other domains do not interfere. Absent interference, the hope is to transduce one sort of potentiality (electrical, in the heart) into another (biographical, into the future; on transduction, see, to start, Helmreich 2007). This modulating of the quantitative present into the qualitative future operates differently from the temporal logics highlighted in recent anthropological examinations, which, drawing on Deleuze, often concern themselves with futures made of unexpected "becomings" (Haraway 2008; Jensen and Rödje 2010; Kirksey and Helmreich 2010). The future in EKG projects is, ideally, knowable within parameters. An EKG can be used to predict what the future might hold, to deliver a prognosis about what potential a person's heart might have (see De Bacquer et al. 1998 for a general study on this topic). Keeping such potentials in line leads not to becoming but to continuing. Interference is not so much, then, a matter of unexpected becomings but of what Tom Boellstorff (2007) has theorized as "coincidence," the accidental convergence of temporalities. Potentials sit within fields of power—electrical, chemical, social, political, economic—and these fields can intersect in happenstance ways with the realization of bodily potentials. The intercalation of different scales of potential—cellular, biographical—opens up spaces of possible rupture; potentiality in practice is not the same as potentiality in theory.

Brain

As with the heart, scientists and doctors have characterized a range of wavy activity for the brain from the level of the single neuron on up. What is described in layperson terms as a "brain wave" is an oscillation of electrical potential in a large swath of neural tissue. Neurons, which carry electrical charges, are constantly buzzing with activity, generating action potentials ("firing") when their charges change, primarily as a result of chemical and electrical stimulus (chains of ions leap from one neuron to another in an electrical current). Aggregates of thousands or more neurons may change their potentials in synchrony, and this change can generate waves through the medium of the neural tissue. Such oscillations are represented using EEGs, tracings graphically resembling EKGs, that graph voltage fluctuations between electrodes placed at different positions on the scalp, surface locations that can pick up a trace of what is happening deeper inside the head.

The EEG was invented in the 1920s, in Germany, by Jena psychiatrist Hans Berger, who proposed that EEG traces were evidence that mental processes were physiological processes,

9. See https://wiki.engr.illinois.edu/display/BIOE414/History+of+the+Implantable+Cardioverter+Defibrillator (accessed November 2, 2012). Compare Friese (2013) and Svendsen and Koch (2013), which examine how nonhuman animal species continue to be employed as stand-ins for humans.

not ethereal, impossible to pin down phenomena (Borck 2001, 2008). Some of his contemporaries sought to go further, believing that EEGs could be used to access the content of cognition itself, even suggesting the classification of personality types, a hope that has surfaced now and again in the long history of popular receptions of the EEG. Berger himself became interested in using EEGs to diagnose epilepsy, a condition that turned out to be characterized by frequent spiking in the wave train. When the EEG technique traveled to the United States, it fit well into American progressive-era hospital worlds, geared toward the production of standardized records that could be used in managerial approaches to the administration of patients and other medical subjects (Kroker 2007:261). As Daston and Galison (2007:322) point out, however, the EEG's use as a vehicle for "mechanical objectivity" was tempered by most of its medical users' contention that only those with trained judgment could render a proper reading. That trained judgment then plugged the EEG into debates around such political topics as asylum reform. The use of EEGs to diagnose epilepsy—and to designate it as a foundationally physical pathology—placed the technology within a biopolitical frame that sought to know the truth of brains through trained objective rather than subjective reports.

As the EEG was refined, biomedical practitioners from psychiatrists to sleep scientists used it to classify several different brain-wave patterns characterized by distinct frequency ranges. Beta waves, from 13 Hz to 30 Hz, mark people who are awake and alert. Alpha waves operate between 8 Hz and 13 Hz; they characterize people who are relaxed, with eyes closed.[10] Theta waves, from 4 Hz to 8 Hz, correlate with sleepiness. Delta waves, at 4 cycles or fewer per second, are associated with sleep; they are also observed in young, awake, babies and in coma patients (see fig. 2).[11]

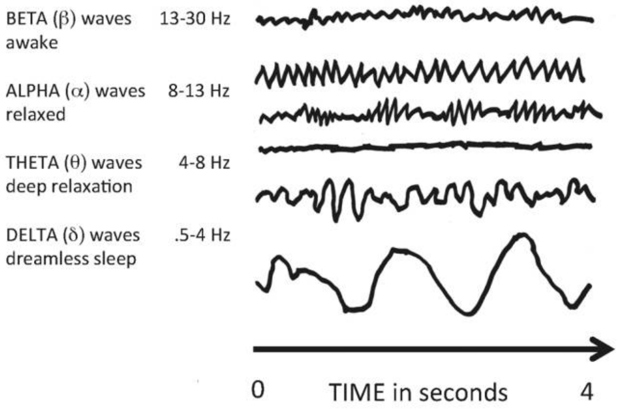

Figure 2. Taxonomy of EEG brain waves. Modified and adapted from Malmivuo and Plonsey (1995, fig. 13.5; http://www.bem.fi/book/index.htm), with specification that "all the material of this Web edition is free for publishing elsewhere."

The social life of EEGs transformed when they were patched into a cybernetic view of the organism and used not just to classify epileptics and others but also to develop therapies through which brain waves might be used as stimuli for individual self-regulation and feedback. In the 1970s, Barry Sterman, a doctor at the University of California, Los Angeles, found that it was possible to train persons with epilepsy to modulate their brain-wave activity by following EEG-based prompts to relax (Pretor-Pinney 2010:60). Now, potentiality would not be simply a latent force to be recognized but would be one that could be explicitly worked on, one that might be plastic to social and personal intervention. Regulating quantities might permit the managing of qualities.

The term for such self-regulation is "biofeedback," a word that first made it into print in 1970 in the *Journal of Transpersonal Psychology*. Here, the story arcs away from the domain of establishment neurophysiology and travels into the realm of 1970s American counterculture, where EEGs gather attachments to new meanings of "potential" that are then ported back into more mainstream brain research.

"Biofeedback" took off in the 1970s and sought to place individual persons in the loop of monitoring and controlling the waves of activity in their bodies, particularly their brains. As Andrew Pickering (2010) and Nicolas Langlitz (2013) have

10. The first sort were named by Berger; the "alpha" designation reflects this and not some ordinal correspondence of letters with frequency.

11. Sleep, meanwhile, also had a set of characteristic wave traces. In so-called "slow-wave" sleep, the brain produces ponto-geniculo-occipital (PGO) waves—electrical pulses that travel from the brain stem to the portion of the brain responsible for processing retinal signals and on from that location to the visual cortex. PGO waves, registered on EEGs, are treated as evidence for REM sleep. "Kleiman and Aserinsky used the EEG to show not only that rhythmic eye potentials were not artifacts of bodily movement or of EEG but that these potentials were clearly related to a low-voltage brain wave pattern" (Kroker 2007:317).

Sleep, measured and administrated, unfolded through a biopolitical process in which sleep was "made abstract" (Wolf-Meyer 2008). As Kenton Kroker (2007) puts it, EEGs were used "to separate sleep from the sleeper" (292). A series of "stages" came to characterize sleep: "The idea that sleep came in cycles of distinctive stages developed between 1934 and 1937. The first few articles to appear in *Science* and the *Journal of Experimental Psychology* simply announced the discovery of a number of new kinds of brainwave. . . . There were 'trains' or regular 10-per-second waves, 'spindles,' which were short bursts of activity in a low-voltage background, slower, 'saw-toothed' waves with a high voltage, and periods of random activity that seemed to have no discernible pattern at all" (Kroker 2007:292).

Sleep, as sociologist Simon Williams (2005) suggests, has become a biopolitical object, its administration keyed to projects of social organization, moral judgment, and economic management. Williams (2005) reports that "slow-wave sleep . . . declines with age from about 20–25 percent of total sleep in early childhood to less than five percent by middle ages, with old people getting precious little slow-wave sleep. Sleep becomes more fragmented with advancing years with more frequent awakening and a circadian shift to a more 'lark-like' pattern" (78). These transformations are not the "natural" basis on which society is organized but are rather in interdependence with political economic processes involving everything from changing household organizations; gendered divisions of labor and public/private, ethnic segmentations of labor and of neighborhoods; and so on.

detailed, interest in biofeedback emerged in sync with countercultural imperatives to explore altered states, particularly "alpha-wave dominated states that had become identified with transcendental experiences" (Pickering 2010:83). Such mobilizations of EEGs dovetailed well with the aims of such ventures as the "human potential movement," a countercultural enterprise centered at the Esalen Institute in Big Sur, California, dedicated to joining the latest science (often cybernetic in flavor) with "Eastern" and other alternative spiritual approaches to experience (Kaiser 2011). In her "Biofeedback, Voluntary Control, and Human Potential," psychologist Patricia Norris (1986) offers an initiate's history of biofeedback that demonstrates just this weaving together of interests in Eastern mysticism, transpersonal psychology, and self-regulation. Such links have had a long legacy. Biofeedback devices of varied descriptions continue to be created to permit people to monitor their own brain waves (Dumit 1995), promising, for instance, to help aspirants achieve meditation without any of the cultural training and less of the self-discipline that might come with becoming, for example, a Yogi. Such promises, one might conjecture, also connect to an impulse to transcend the biological, delivering an account of embodiment that operates not in the realm of flesh but in the realm of physics and formalism. The doubleness of waves—as material processes as well as formal abstractions—does cultural work here, inviting a materialist explanation of subjectivity that simultaneously operates in a weirdly disembodied, even metaphysical way.

Biofeedback is still going strong. The Association for Applied Psychophysiology and Biofeedback these days defines the practice as

> a process that enables an individual to learn how to change physiological activity for the purposes of improving health and performance. Precise instruments measure physiological activity such as brainwaves, heart function, breathing, muscle activity, and skin temperature. These instruments rapidly and accurately "feed back" information to the user. The presentation of this information—often in conjunction with changes in thinking, emotions, and behavior—supports desired physiological changes. Over time, these changes can endure without continued use of an instrument. (http://www.aapb.org/i4a/pages/index.cfm?pageid = 1)

In 2012, the association hosted its 43rd annual meeting, "Evoking Human Potential"—a clear link back to the human potential movement. In this connection, biofeedback promises that people can reach into a well of preexisting potential—in the brain, heart, and so on—and harness it for biographical potentials. Potential as latent force is made technologically and representationally explicit so that it can be acted on as persons seek to choose possible personal futures.

More technically tuned descendants of biofeedback machines are in the works with contemporary "brain-computer interfaces" (BCIs). BCIs are meant to facilitate direct communications between the brain and a computational device. Against the avowedly spiritual cast of 1960s and 1970s attempts to move EEGs into personalized settings, such new work almost always has an institutionally framed medical or ameliorative aim.[12] University of Tübingen neuropsychologist Niels Birbaumer works to train epileptics to forestall their occasional episodes by having them regulate, through watching direct EEGs of their brains, their slow cortical potentials. Birbaumer has also sought to train paralyzed people to control their brain waves to generate signals that can be interpreted in a binary way, such that they might control a computer cursor (see, e.g., Iverson et al. 2008). That sort of BCI might be used to help people living in total paralysis (such as those with amyotrophic lateral sclerosis [Lou Gehrig's disease] or those who have suffered major strokes or spinal injuries) to communicate using minimal motor or cognitive effort. BCIs, for Birbaumer and colleagues, offer communicative possibility to people with "locked-in syndrome," people who are aware but who because of paralysis cannot move their bodies and so have limited to nonexistent means to communicate. In these practices, persons are rhetorically separated from their brains and then imagined as occupying some Archimedean point "outside" their brains from which they can control their neurological function.

Birbaumer has developed something he calls the thought translation device (TTD), a computer program that takes input from an EEG that users can modulate to select letters from an auditory or visual display (Birbaumer et al. 2003). Birbaumer's TTD is meant to transform electrical potential into biographical, social potential. Slow cortical potentials are leveraged into projects that promise the potential for improved quality of life (see also Yuan et al. 2010). The grander promissory aspects of such projects still generate hyperbole, of course, often in a salvific register that will be familiar to students of the promissory biosciences. As one boosterish website has it, "Brain Computer Interface technology will help define the potential of the human race. It holds the promise of bringing sight to the blind, hearing to the deaf, and the return of normal functionality to the physically impaired" (http://www.braincomputerinterface.com/).[13]

12. While BCI could refer to devices known as neuroprosthetics (such as cochlear implants, which aid deaf people in conjuring a simulacrum of hearing), I use it narrowly to refer to devices that are not so invasive.

13. In *What Should We Do with Our Brain?* philosopher Catherine Malabou (2008) suggests that recent discourses about "plasticity" in neuroscience posit a model of cognitive governance distinct from earlier, top-down models of cognition. While the metaphor of the plastic brain—rather than the "hardwired brain"—is coincident with the rise of new species of capitalism that call for flexible specialization, Malabou argues that this metaphor is not chained to its social correlate; if flexibility is about submitting, plasticity is about adapting. Malabou argues that the plastic brain offers resources for intervening in how "we" realize our brains in practice. That claim, it seems to me, smuggles a naturalized/politicized trope of potentiality into the ontology of the brain. As Tobias Rees (2010) has argued based on his fieldwork with neuroscientists developing and advocating a "plastic" view of the brain, an implicit ethic—one of promise—travels along with such accounts (see also Rees 2011).

But where there are electromagnetic waves, interference is never far behind, and this is the case when it comes to thinking with and through brains, too. In "The Invisible Topography of Power: Electromagnetic Fields, Bodies and the Environment," Lisa Mitchell and Alberto Cambrosio (1997) discuss how "low frequency electromagnetic fields emitted from power lines, computers and electrical appliances have become a form of environmental pollution," with people describing their bodies as at risk from their immersion in a "sea" of artificial electromagnetic fields. In the case Mitchell and Cambrosio discuss, which draws on evidence from public hearings in Quebec from 1983 to 1993 on the health effects of electromagnetic fields, a wide variety of players—"physicists, parents of children with leukaemia, public policy analysts, epidemiologists, New Age followers" (Mitchell and Cambrosio 1997:224)—worry about, among other things, the possibility that brain tumors and cancers might be connected to their ambient electromagnetic environment. The boundaries between bodies and environments blur in this "bioelectromagnetic" world—a term that suggests that borders between nature and culture are rearranging, so that "life" sits in a constitutively wavy world (Ribot 2009). In this kind of environment, electric potential and life potential are entangled.

Rhythmanalysis, Time, and Potentiality

Within the electric potentiality hooked into cardiac and brainwave monitoring and management in the service of potential life there unfolds the intercalation of two kinds of time: small-scale cyclical and biographical linear. How shall we understand this dynamic?

In *Rhythmanalysis*, Marxist philosopher Henri Lefebvre (2004 [1992]) outlines a theory of social action and transformation that places rhythm at its center and that is concerned with precisely this relation between the cyclical and the linear. He writes that the "human body is the site and place of interaction between the biological, the physiological (nature) and the social (often called the cultural)" (Lefebvre 2004 [1992]:81). Defining rhythm as measured repetition at a frequency (and always with some variation, some difference), Lefebvre (2004 [1992]) also suggests that social analysts map the intersections of bodily rhythms ("respirations, pulses, circulations, assimilations" [5]) with those of everyday social life ("rites, ceremonies, fetes, rules, and laws" [6]). Mapping the various relations between cyclical and linear, bodily and social, has the aim not of arriving at abstract generalizations about rhythm—that would be, Lefebvre suggests, a simple exercise in "ideology"; social rhythms, after all, are products of social orders. The aim is rather to listen for disruptions, "arrhythmias," places where processes of work and governance fall out of step, out of sync. I have hoped to suggest here that especial attention to electricity and to waves can afford fresh ways of listening both for alignments as well as misalignments between rhythms of potentiality.

Such attention also gives us a possibly different history with which to think about the potentials of human biology, a history that reaches back not just to histories of biology but to histories of physics and to the rise of electromagnetic accounts of the body and the world. Rereading the Galvani-Volta debate about animal electricity (Bernardi 2001; Piccolino 1998) may afford unexpected genealogies for today's electromagnetic body, as may a review of discussions between Lord Kelvin/William Thompson and his brother James Thompson about the electromagnetic fields within which human bodies are located (see also Winter 1998 on the rise and fall of "mesmerism"). What Walt Whitman called "the body electric" in 1855 (just 6 years after Hermann von Helmholtz clocked the first nerve impulse) is a body that might be newly investigated for what it can tell us about the circuits of power within which many of our hearts and minds now live, circuits of potential that have many possible pasts, presents, and futures, many time lines that can reinforce as well as interfere with one another.

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