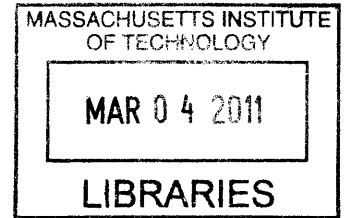


Crafting Life: A Sensory Ethnography of Fabricated Biologies

by

Hannah Sophia Roosth

Bachelor of Arts
Rice University, 2003



Submitted to the Program in Science, Technology, and Society
in Partial Fulfillment of the Requirements for the Degree of

ARCHIVES

Doctor of Philosophy in History, Anthropology, and Science, Technology and Society
at the
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September 2010

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A handwritten signature in black ink, appearing to read "Hannah Roosth".

Signature of Author: _____

History, Anthropology, and Science, Technology and Society
August 10, 2010

Certified by: _____

Stefan Helmreich
Associate Professor (Anthropology)
Thesis Supervisor

Certified by: _____

A handwritten signature in black ink, appearing to read "Michael M.J. Fischer".

Michael M.J. Fischer
Andrew W. Mellon Professor in the Humanities;
Professor of Anthropology & Science & Technology Studies (Anthropology & STS)
Thesis Committee Member

Certified by:

11

Heather Paxson

Class of 1957 Career Development Professor

Associate Professor (Anthropology)

Thesis Committee Member

Certified by:

[Handwritten signature]

Susan Silbey

Leon and Anne Goldberg Professor of Humanities;

Professor of Sociology and Anthropology (Anthropology)

Thesis Committee Member

Accepted by:

[Handwritten signature]

David Kaiser

Associate Professor, STS

Director of Graduate Studies, History, Anthropology and STS

Accepted by:

[Handwritten signature]

David A. Mindell

Dibner Professor of the History of Engineering and Manufacturing

Professor of Aeronautics and Astronautics

Director, Program in Science, Technology, and Society

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ABSTRACT

This ethnography tracks a diverse set of practices I term “constructive biologies,” by which I mean efforts in the post-genomic life sciences to understand how biology works by making new biological things. I examine five fields of constructive biology — synthetic biology, DIY (do-it-yourself) biology, hyperbolic crochet, sonocytology, and molecular gastronomy — investigating how they are enmeshed in sensory engagements that employ craftwork as a means of grasping biology. *Synthetic biology* is a community of bioengineers who aim to fabricate standardized biological systems using genetic components and manufacturing principles borrowed from engineering. *DIY biology* is a community of “biohackers” who appropriate synthetic biologists’ terminologies, standards, and commitment to freely exchanging biomaterials in order to do hobbyist biological engineering in their homes. *The Hyperbolic Crochet Coral Reef* is a distributed venture of thousands of women who are cooperatively fabricating a series of yarn and plastic coral reefs in order to build a material simulation of oceanic morphologies and evolutionary theories. *Sonocytology*, a technique in nanotechnology research, uses scanning probe microscopes to “listen to” cellular vibrations and “feel” the topologies of cells and cellular components. *Molecular gastronomy* is a movement in which practitioners — physical chemists and biochemists who study food, and chefs who apply their results — use biochemical principles and laboratory apparatuses to further cooking and the culinary arts. In analyzing these fields, I draw on histories of experimental biology, anthropological accounts of artisanship, science studies work on embodiment and tacit knowledge in scientific practice, and sensory ethnography. Based on data gathered from participant-observation and interviewing, I argue for thinking about making new biological things as a form of “crafting,” an analytic that illuminates five aspects of contemporary biological manufacture: 1) sensory cultivation, 2) ongoing participation with biological media and forms, 3) the integration of making biological things and practitioners’ self-making, 4) the embedding of social relations, interests, norms, and modes of exchange in built artifacts, and 5) the combination of making and knowing. In this study, I argue that both biology the substance and biology the discipline are currently being remade, and that increasingly, life scientists apprehend “life” through its manufacture.

Thesis Supervisor: Stefan Helmreich

Title: Associate Professor of Anthropology, Massachusetts Institute of Technology

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University utterly transformed the way I thought about science and technology, and helped me realize that what I had thought were my own idiosyncratic interests were in fact at the heart of a rich and exciting academic discipline. They were also decent enough only to laugh a little bit when I mistook the phrase “Open Source” for “open sores.” Other professors at Rice presided over my rites of passage into anthropology: I first read Foucault, Deleuze, and Derrida with James Faubion, who illuminated social theory, making it seem both potent and comprehensible. Nia Georges guided and funded my first foray into ethnographic fieldwork in Rhodes, Greece. In my first years at MIT, my thinking was sharply torqued by Joe Dumit and Evelyn Fox Keller. Joe taught me how to read both critically and generously. Evelyn Fox Keller, sage of all things biological, continues to inspire and shape my thinking and writing.

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I presented early drafts of parts of this dissertation at several academic conferences. My earliest work on synthetic biology was presented in 2006 in a panel organized by Natasha Myers at a meeting of the Society for Literature, Science, and the Arts. I presented sections of Chapter 3 in the STS Circle at Harvard, and thank Sheila Jasanoff for inviting me to speak there. Parts of Chapter 6 were presented at the annual meeting of the Society for Cultural Anthropology in the “Eating NatureCulture” panel; I thank Heather Paxson for organizing this panel and Brad Weiss for his astute commentary on my paper. I thank the discussants, co-panelists and audiences at these presentations, as well as other talks given at the Max Planck Institute for the History of Science, the Society for the Social Study of Science, the International Conference Mutamorphosis, and the annual Synthetic Biology meeting, for their valuable feedback and critique. I practiced several of the above presentations in HASTS writing workshops, which were organized by Chihyung Jeon, Xaq Frohlich, and David Singerman. I also thank the anonymous reviewers of *Critical Inquiry* for their close reading of an early version of Chapter 5. Undergraduate students in the Fall 2009 “Art Craft Science” course read ethnographies of craft practice alongside me, and their ruminations on the intersections of science and craft impacted my thinking during early stages of writing.

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Finally, a different sort of acknowledgements may be found at the end of this dissertation. For the last ten years, I have thought through and with the texts listed in the bibliography. Though the authors indexed there are too numerous to acknowledge here, I thank them for opening up a conversation in which I am thrilled to participate.

Chapter 1. Introduction

Sitting at his computer in a basement laboratory in Los Angeles, a graduate student feeds a bit of data he gathered from a jerrybuilt atomic force microscope into a freeware program downloaded from the Internet. He turns up the volume and listens, unmoving, as the vibrations of yeast cells are rendered in thumps and hisses. In her home in rural Texas, a middle-aged woman sits up with her dogs until three in the morning, using a geometrical modeling technique to crochet models of marine life forms. Feeling them take shape in her hands, she thinks about evolution, anthropogenic climate change, and differential rates of organic growth. In a bioengineering laboratory at MIT, a zealous crew of undergraduates uses ready-made genetic components to modify the olfactory properties of that experimental workhorse, *E. coli*. After months of development knocking out some biosynthetic pathways and stirring in others, another student walks into the lab's warm room one August morning to find the aroma of freshly baked banana bread. A few blocks away in an unlabeled hacker workspace, a technogeeky collective of computer programmers, biologists, transhumanists and other gainfully unemployed folk isolate human DNA using bits and bobs from their kitchens — gin, meat tenderizer, and soap. When the DNA becomes visible, they hold test tubes up to the light, flabbergasted by being able to see the white filaments clumped in clear solution. In a restaurant kitchen in England, teams of interns (each dyad a scientist paired with a chef) rejig laboratory equipment intended for biology labs — sonic pulses, vacuum centrifuges, and plasma freezing systems — to concoct new dishes. In doing so, they acknowledge that the stuff we eat is made of the same biological substances

(amino acids, lipids) that are routinely manipulated in biology labs, and that the armory of experimental biology can be not only epistemologically productive, but delicious. I suggest in this dissertation that something new is afoot in the life sciences, and that that newness is emblemized by the heterogeneous practices I have just sketched.

The backdrop to these episodes is biology at the beginning of the twenty-first century. The end of the twentieth century was, by all accounts, a moment in which biologists felt that biological discoveries allowed them to control biology with increasing power and precision. In the mid-1970s, brief moratoria on recombinant DNA technology capitulated to widespread use of this approach, which allowed researchers to move genetic material between different species.¹ The development of the polymerase chain reaction (PCR) in the early 1980s meant that biologists could not only sequence, but also synthesize genetic material. Firm relations between research and industry, spurred by seismic shifts in the status of biological things in U.S. patent law and governance, spawned biotech companies such as Cetus, Genentech, and Amgen.² The genetics of the 1980s, which had traded on “gene for” discoveries (cystic fibrosis, Huntington’s disease, sickle cell anemia), had given way to genomics in the 1990s, which sought to sequence the genome in its entirety. Sped-up high-throughput sequencing technologies, matched by vast assemblages of private and public research initiatives, made possible a spate of genome projects.

¹ Further, the self-imposed moratorium drafted during the Asilomar Conference of 1975 led biologists to believe that they not only could control biology, but also themselves.

² Most notably, the Bayh-Dole act of 1980, which allowed technology transfer between academic research and industry, and the ruling in *Diamond v. Chakrabarty* in the same year, which allowed genetically engineered organisms to be patented in the U.S., distinguishing between “things of nature that occur naturally” and “things of nature that occur by man’s handiwork” (Sherwood 1990: 47, quoted in Hayden 2003: 26).

Hybrid, transgenic, and cyborg biological entities — Dolly, OncoMouse, and the Flav-R-Savr tomato, for example — made headlines and worried ethicists.

But then, as Evelyn Fox Keller put it, a “funny thing happened on the way to the holy grail” (1995: 22). The discourse of gene action had figured DNA as code for half a century (Kay 2000), but faced with all this source code, geneticists and genomicists were at a loss as to what came next. Instead of the genome, biologists began trying to map proteomes, metabolomes, expressomes, and interactomes, as bioinformatics enabled growing amounts of information to be databased and analyzed. Systems biology rejected reductionist models of biology, asking how biological forms and processes take shape in complex multi-scalar interactions. While some life scientists aver that biology since the genome projects is contiguous with the sequencing race, that synthesizing is sequencing’s logical successor, it seems instead that substance has returned to the life sciences, that we have returned from a two-dimensional “flat” biology to a more dynamic, embodied, and processual — a *messier* — version of what constitutes life, from post-transcriptional cascades, to epigenetic inheritance, to three-dimensional protein conformations. This return to “liveliness” in turn demands of life scientists an embodied and intra-active engagement with biological stuff (Myers 2006, 2008).

Constructive biology — by which I mean efforts to grasp how biology works by making, and more specifically, *crafting*, new biological things — is the rejoinder to biologists’ and

biotechnologists' efforts to control biology. With the materialist return to living substance following the genetic fetishism of the 1980s and 1990s, I describe how some people have fastened upon a constructive approach to doing biology. Making new biological things is, for them, the royal road to understanding biology. This hands-on approach to biology now entails an experiential or sensographic register — not just looking at living substances, but smelling, listening, tasting, touching. Further, it is “post-organismic,” in that researchers do not think about biology at the level of whole organisms, but rather in terms of the experimental and manufacturing techniques they use. That is, they identify their particular tactics or methods as inherent in biology prior to their own interventions. Distinguishing this sort of manufacture from other forms of making — making as control, as design, as synthesis — I recognize it as a mode of craft practice.

Drawing on anthropologists of craft and artisanship and craft critics, I suggest thinking about making new biological things as a form of “crafting,” an analytic that illuminates aspects of biological manufacture that can be concealed by actors' categories of biological work as control, design, or synthesis. I use craft to illuminate five important trends in the historical turn to biological manufacture I have just outlined: 1) sensory cultivation, 2) ongoing participation, 3) the integration of making things and self-making, 4) the embedding of social relations, interests, and values in manufactured artifacts, and 5) the combination of making and knowing. First, practitioners acquire and embody technical and practical knowledge through practice. Sociologists of science who have taken up how scientists engage in the hands-on work of laboratory science have examined how researchers learn and hone scientific sensibilities through

practice (Collins 2001, Polanyi 1962).³ I argue that thinking about biological manufacture as craft highlights how tacit knowledge and intuition can emerge from cultivating the senses in a laboratory context, how knowledge “is absorbed by means of the sense organs and muscles” (Feibleman 1966: 328), suggesting that science studies scholars also should mind how non-visual senses figure in scientific work. Heather Paxson terms this craft-based sensory engagement a “synaesthetic sensibility,” by which she conveys how artisans’ practical actions are directed by “sensory evaluation” of materials (forthcoming). While “control” and “design” conjure an authoritative distance and dominance over biological matter, thinking about how senses of taste, touch, and hearing are tuned towards biological apprehension exposes how researchers’ sensoria and biotic sensescapes are co-constructed in encounter. Second, thinking about biological manufacture as crafting makes apparent that making biological things means an active ongoing participation with biological media and forms in which practitioners struggle towards proficiency. Control and design, in contrast, imply that the work of building biological things gets done project-by-project, in which researchers follow formalized design principles or deductive methods, obscuring the open-ended, processual, and sometimes unpredictable nature of biological manufacture. Third, in the process of learning how to craft things, artisan apprentices also learn the social values, terminologies, and dispositions of their community of practice (Herzfeld 2003, Kondo 1990, Terrio 2000). These artisanal identities are bound to materials and tools, but also to places. Thomas Gieryn writes of laboratories, “built places materialize identities for the people, organizations, and practices they house” (1993: 423; see also Kohler 2002, Traweek 1988). Thinking about biological manufacture as “craft” requires

³ I review this literature in greater detail below.

tracking not only professional but also hobbyist science, looking for how artisanal identities are forged by working with biological media or theories outside of professional scientific locales. Fourth, it means tending to crafted biotic artifacts, which embed social norms, values, tastes, and modes of exchange. Fifth, focusing on biological manufacture as craft practice foregrounds how the work of making biological things combines empirical and theoretical knowledge, such that practical interventions into biological matter also generate new knowledges about biology.

In this thesis, I take the pulse of the contemporary biosciences by identifying and exploring a diverse set of practices I think of as “constructive biologies.” I examine five fields of constructive biology — synthetic biology, DIY (do-it-yourself) biology, sonocytology, molecular gastronomy, and hyperbolic crochet — asking how they are enmeshed in sensory engagements that employ craftwork as a means by which to grasp biological stuff. *Synthetic biology* is a community of bioengineers who (Chapter 2) aim to fabricate standardized biological systems using genetic components and manufacturing principles borrowed from engineering. Proponents of synthetic biology, such as those at the Massachusetts Institute of Technology Department of Bioengineering, where I did fieldwork between 2005 and 2007, have garnered governmental funding, venture capital, and public attention for their research agenda. They seek to accelerate and industrialize the kind of bioengineering done in the 1980s and 1990s. First by removing genetic components to “streamline” genomes for ease of design; second by articulating a set of community-approved rules that set standards for how new genetic components are synthesized. *DIY biology* (Chapter 3) is a community of 850 “biohackers,” most of whom are American, who appropriate synthetic biologists’ terminologies, standards, and Open Source commitments to do

hobbyist biological engineering in their homes. They meet both in person and online, sharing protocols for performing basic bioengineering techniques, such as gel electrophoresis and DNA extraction, without the benefit of laboratory infrastructures. Their aim is to argue that non-professionals are entitled to work with biological media and tools. *The Hyperbolic Crochet Coral Reef* (Chapter 4) is a craft project coordinated by the Institute for Figuring in Los Angeles. Thousands of women from Europe, the U.S., Asia, and Australia are crocheting physical models of hyperbolic geometry, a kind of non-Euclidean plane whose shape many marine organisms embody. They do so in order to craft a material simulation of oceanic morphologies and evolutionary theories. Their work is displayed in both science museums and art galleries. *Sonocytology* (Chapter 5) is a technique developed by James Gimzewski, a nanoscientist in UCLA's Department of Chemistry and Biochemistry. His lab modifies scanning probe microscopes, which are usually used to manufacture and analyze nanostructures, instead to "listen to" cellular vibrations and "feel" the topologies of cells and cellular components. *Molecular gastronomy* (Chapter 6) is a movement of chemists and chefs in Western Europe and the U.S. who import laboratory techniques and biochemical principles into the kitchen, where they use tools such as "gelling agents from seaweeds and bacteria, non-sweet sugars, aroma extracts, pressurized gases, liquid nitrogen — to bring new forms of pleasure to the table" (McGee 2004: 2). Advocates of molecular gastronomy work in both laboratories and kitchens. Some study the principles underlying food preparation; others apply research findings and techniques to the invention of new dishes with scientific and futuristic aesthetics.

I have ordered the chapters so that, though aspects of both crafting and sensing are woven throughout, the argument moves from crafting to sensing. Chapters 2 and 3 function as a set that explores insider and outsider communities who build biological things, while Chapters 4, 5, and 6 more squarely address people who use non-visual senses (touch, hearing, and taste, respectively) to apprehend biological things. The final chapter asks what changes in biology these fields might be diagnostic of, and draws on my subjects' research practices to contemplate ethnographic methods. Instead of participant observation, I offer *participant-sensation* as a model for anthropological fieldwork.

My first claim is a theoretical one. Simply put, I argue that for the participants in each of these fields, the work of *making* offers a kind of understanding of biological things that would not otherwise be accessible to them. This is readily apparent among synthetic biologists and DIY biologists, for whom wanting to make something work and wanting to know how it works are paired questions. Among Hyperbolic Crochet Coral Reef (HCCR) crafters, making crocheted objects is a way of grasping theories of evolution and thinking through folk understandings of mutation and morphogenesis. Sonocytologists, in building their microscopes from scratch, end up doing serious thinking about the phenomenology of nanoscientific instrumentation and apprehension, and its attendant implications for the cells and cellular components they study. While soldering and welding, for example, they talk about the difference between touching and not touching and whether they are “really” touching cellular components. The technically mediated human sensorium — assemblages of hands, eyes, ears, mouths, noses, and microscopes — and the biological object here materialize in reference to one another through researchers'

hands-on work. If, as Ian Wilmut, Dolly the sheep's maker, claims, her birth announced the beginning of the "age of biological control" (Wilmut, Campbell, and Tudge 2000, quoted in Franklin 2007), I describe an "age of biological construction."

This ethnography is also meant to make a methodological intervention. I argue that both biology the substance and biology the discipline are currently under construction, and that biological research is now done by different people, in different locales, and for different reasons than science studies scholars are used to studying. This turn requires that anthropologists, sociologists, and historians retool their own research design to admit and account for such changes. A seemingly idiosyncratic throng of people are at the heart of this dissertation — degreed and tenured scientists, yes, and grad students and postdocs on the academic treadmill, but also a handful of chefs, a noisy swarm of hackers and dropouts, backyard, garage, and amateur kitchen scientists, artists and science communicators, not to mention an assortment of crafty women brandishing crochet hooks in a campaign against climate change. Two of my fieldsites are clearly internal to science (synthetic biology, sonocytology), two are external to it (DIY biology, the HCCR), and one (molecular gastronomy) mixes professional scientists with craftspeople. Sociologists have demonstrated that the boundaries between "science" and "the public" are unstable, negotiated, and malleable (Gieryn 1983, 1999). Not everyone who claims to be doing science really is, but beyond inside/outside definitions of scientific work put in place by scientists themselves, I argue that tracking scientific things or scientific techniques, rather than science *per se*, opens up for investigation the less normative ways people actively engage with science as a craft or hobby. By paying attention primarily to those people who are

identified by their peers as scientists, science studies scholars risk missing an important aspect of scientific culture, one that does not sit neatly in either the category of “legitimate” scientific practice or “public participation in science.” A second but related point is that I think the “cultural boundaries of science” (ibid) are becoming less like boundaries and more like semipermeable membranes across which some techniques, rhetorics, equipment, and people shuttle back and forth.

In what follows, I first narrate how I came to this study, explaining a few of the biographical idiosyncrasies that drew me to this project and helped crystallize it. I next trace four scholarly literatures with which this dissertation is engaged: the history and anthropology of the life sciences, the practice turn in social studies of science, anthropological treatments of craft and artisan practice, and the school of “sensory ethnographers” who aim to write more “sensugraphic” or “emplaced” accounts of cultural activity. I close this chapter with an outline of the dissertation.

METHODOLOGY

As an anthropologist, I am interested in social relationships and social practices, how the two are entangled, and how they are formed within and informed by shifting contexts of power, interests, imaginaries, and ideologies. I came of age in the “age of biological control,” starting high school the year Dolly the sheep was born and entering college the year the sequencing of the human genome was announced. Steeped in these millennial stories about kinship, identity, and genealogy, it has seemed common sense to me that the products of the life sciences are powerful

brokers of social formations and relations. As I delved into the anthropological literature, I found that feminist anthropologists of science writing about reproductive technologies and biotechnology had examined how biological knowledge speaks to and shapes lived experience and ways of arbitrating nature and culture (Franklin 1997; Franklin and Ragoné 1998; Franklin et al. 2000; Haraway, 1989, 1991, 1997; Strathern 1992a, 1992b). As Sarah Franklin puts it, “Stakes remain high in the pursuit of a knowledge of knowledge, the nature of nature, the reality of reality, the origin of origins, the code of codes” (1995: 166). This project grew out of my curiosity about how biology — the discipline of the life sciences and the stuff that is its object — animates and figures in contemporary notions of relatedness and exchange, substance and affect, identity-making and value, and more phenomenological questions about how we engage with and make sense of the natural world. Further, I was driven by the question of how the theoretical object of biology, namely “life,” is currently being reworked, its contours penciled, redrawn, and modified as new biological things are *made*.

This dissertation is based on anthropological fieldwork conducted from 2005 to 2009. As an undergraduate, I wrote my senior thesis on “bioartists” who use biotechnical techniques and living substances to build art installations. This early project focused on how non-scientists adopted the trappings of biotechnology, and how art audiences experienced biotech first-hand, by seeing, touching, and eating the products of laboratory biology (such as transgenic rabbits and “meat” tissue cultures). Then, as now, I was intrigued by what happens when biology’s objects leave the laboratory and circulate in other cultural fora. Hannah Landecker, my undergraduate advisor, had guided my study of bioart and showed me the website of the Synthetic Biology

Working Group at MIT, which at the time consisted of little else. Synthetic biologist Drew Endy had just joined MIT as a fellow in 2002, and when Landecker showed me the website, undergraduate students were in the midst of MIT's first winter term synthetic biology course, for which they designed "Genetically Engineered Blinkers" (Ferber 2004). Fresh from writing about art exhibits in which bacteria, cacti, and rabbits had been genetically engineered to glow green in the name of art, I was fascinated by these MIT students who spent their January holidays holed up in a lab constructing *E. coli* to "blink like a lighthouse" (ibid). I decided to study synthetic biologists in hopes of learning what kinds of hybrid biotechnical "boundary objects" (Star and Griesemer 1989) took shape in the "trading zone" (Galison 1997) linking engineering and biology. How were computational metaphors getting built into biotic things, and what cultural residues could be discerned in them? How did these new alliances between experimentation and manufacture play out in lab practice, in peer review, in intellectual property rights? If biology was here being "enterprised up" by turning it into something partible and standardizable, what biological and cultural enterprises did such work assume (Strathern 1992a)? MIT's Synthetic Biology Working Group would become the fieldsite in which I spent the longest time. DIY biology, in many ways a Cambridge offshoot of synthetic biology, germinated while I was doing fieldwork among synthetic biologists. It offered me a field in which I could extend the above questions, but think through hobbyists' attempts to engineer biology in terms of what philosophers of science, most notably Karl Popper (1965), have termed the "demarcation problem" between science and non-science, using theoretical tools from the anthropology of science to examine hobbyist science.

In 2005, a college friend who had also come to MIT to do graduate work asked me to help him DJ a show on MIT's radio station, and though the program was sadly short-lived, its theme — science and music — prompted me to search for an appropriately scientific ambient sound to play at the top of the hour while reading broadcasting announcements. An Internet search turned up the fuzzy hum and crackle of yeast cells, rendered audible in the lab of James Gimzewski at UCLA. The anthropology and sociology of science had taught me to think about science in terms of visibility — as clusters of techniques and practices for making invisible things visible, or inscribing and displaying data (Latour 1987, Latour and Woolgar 1986, Lynch and Woolgar 1990). Seeing cells already may be banal, but hearing cells was my own “epistemological electroshock therapy” (Haraway 1988: 578): visualization promises transparency, but sonification makes mediations and transductions apparent. I was interested in how such soundscapes are constructed and how they impact the way researchers understand their biotic objects of study. I conducted participant-observation research in Gimzewski's lab in the fall of 2008.

After hearing the Institute For Figuring's co-director, Margaret Wertheim, lecture at the American Museum of Natural History in New York, I added the Hyperbolic Crochet Coral Reef (HCCR) to my fieldsites, as it struck me as productively comparative to synthetic biology: people were building physical simulations of organisms, albeit using yarn instead of DNA. Unlike the somewhat masculinist projects of synthetic biology and DIY biology, which seek to master or dominate nature,⁴ this project was advertised as a feminist project, one which explicitly

⁴ For an account of how science has been coded as a masculinist enterprise that seeks to uncover and conquer a passive feminized “Nature,” see Keller 1985.

turned biology into a craft practice. Like members of DIY biology who approach biology as a hobby, this field promised one place from which to think about what happens when biology exits professional fields to become a popular or vernacular object (Dumit 2003, Martin 1994, Rapp 1999). In this field, I visited with Margaret and Christine Wertheim in their Los Angeles home, attended a Reef workshop at the Los Angeles County Museum of Art, and spoke with and interviewed Reef contributors.

My final fieldsite — both in the project's development and chronologically — was among molecular gastronomers in Paris and London, where I conducted fieldwork for four months in 2009. I chose molecular gastronomy as a fieldsite because of its productive analogies and dissonances with my other fieldsites. Its practices are dispersed across an array of experimental, artisanal, and domestic spaces, allowing me to revisit the question of where science is located, and how locales shape scientific and artisanal personae (Galison and Thompson 1999, Kohler 2002, Traweek 1988). Like synthetic biologists, molecular gastronomers' project is about rationalizing and standardizing things in the world (whereas synthetic biologists' found object is biology, molecular gastronomers concentrate on cooking). Alongside the HCCR, this fieldsite is the one most concretely engaged with a craft practice (fiber arts, culinary arts), yet, as we will see, the two articulate gender in altogether different ways. Further, in its attempts to rationalize French cuisine, molecular gastronomy is one example of how national imaginaries are justified and reconfigured through scientific practice (Abu El Haj 2001, Prakash 1999, Rabinow 1999b, Redfield 2000).

“Constructive biology” is an analytic I use to make sense of a complex topography of scientific practices. I borrow the term from synthetic biologists, who market the bottom-up manufacture of biotic systems from component genetic parts as “constructive biology.” The synthetic biology company Codon Devices even trademarked the phrase. Nonetheless, there is no point at which I can point to a particular person, a single technique, or a juicy quotation and say, “here, this is a constructive biology.” Instead I treat constructive biology as emergent in a broader configuration of epistemological commitments, technical, material, and economic infrastructures, and social activities. Because constructive biology is an artifact of my own presence and participation in and analysis of social practices, it is an artifact, something I have crafted in trying to make sense of what is going on in the life sciences in the last decade. So constructive biology is both an analytic and an object of study, one that only emerged in the process of doing fieldwork, interpreting my data, and writing this document. This is fitting, as one of my central claims is that for constructive biologists, making new things is a route to understanding the objects under construction. So too, it seems, for anthropology.

The fieldsites I chose in designing this project arose from the questions I asked. To a greater or lesser extent, the life sciences are now rife with elements of constructive biologies, and if one is tuned into them, they can be discerned in places, practices, and disciplines I do not here explore. That is, while I did not conduct fieldwork in a proteomics lab, or a systems biology department, or among engineers cobbling together bacterial batteries in Rwanda, such locales

also would have been suitable places from which to narrate an account of constructive biology. The fieldsites I chose to visit and explore are not exemplary nor representative of constructive biology, but I do find them both indicative and enlightening in their partiality. This fact makes this dissertation multi-sited in the most practical sense: my research started in Cambridge, Massachusetts, but conveyed me to Los Angeles, Paris, New York, Hong Kong, Zurich, and London (and the busiest metropolis of all, the Internet). It is also multi-sited in the sense articulated by Marcus and Fischer (1986), in that I am writing about something — or a constellation of somethings — that are globalized, variegated, heteroglossic phenomena.

Juxtaposing my fieldsites across a number of axes, certain aspects of constructive biology may be brought into relief. For example, it is worth noting that each of these fieldsites is marked by at least one difference — each of them contains elements of paradigmatic or typical fields in the life sciences, but diverges from them in at least one significant way. Synthetic biology works in biotic substance, but follows design principles (and trades in metaphors) culled from electrical and computational engineering. Biohackers follow routine protocols commonplace in the life sciences (PCR, DNA extraction, electrophoresis, sequencing and synthesis), but execute them outside of institutional infrastructures. The HCCR simulates biotic forms and evolutionary concepts, but in an abiotic substrate (yarn). Sonocytologists work with biotic substance in accredited laboratories, but upend the hierarchy of the senses by using sound and touch as their primary data. Molecular gastronomers use biochemical media, principles, and experimental apparatuses, but the aims of their research are not meant to be applied within science or engineering, but to the craft of cooking.

I incorporated five techniques into my fieldwork: 1) intensive periods of participant-observation, each lasting between 2 months and 2 years; 2) brief targeted visits (lasting a few days to a week); 3) long format semi-structured interviewing; 4) attending and presenting at international scientific conferences; and 5) ongoing surveys of professional peer-reviewed and popular science accounts of each of my fieldsites.

Participant-observation is by its nature an eclectic undertaking. My activities in the field included but were not limited to: chatting, pipetting, soldering, drinking beers, holding stuff when everyone else's hands were occupied, building microscopes, making ice cream, crocheting, isolating my own DNA, chauffeuring grad students lacking driver's licenses, sometimes saying the wrong things at the wrong times, and usually taking notes. What participant-observation entailed was keyed to each of my fieldsites. For example, while conducting ethnographic fieldwork among synthetic biologists, for two years (2005-2007) I attended weekly laboratory meetings and smaller group meetings devoted to issues such as publishing, ethics, and intellectual property. After this intensive stint of fieldwork, I kept up with synthetic biology by attending international annual conferences, public lectures, undergraduate laboratories and graduate seminars. In contrast, participant-observation in the Gimzewski lab was designed differently: to learn more about how researchers constructed soundscapes using technical equipment, I spent most of my time working in the lab, building microscopes and watching

researchers interpret data. My participant-observation among biohackers also had to be tailored to that particular field: though much of my work required my presence at events — attending and participating in DIY biology “meet-ups” and talking to and interviewing group members — much of my research in this field had to be accomplished online, tracking the voluble and lively Internet community of biohackers, whose conversations and arguments are openly accessible. Christopher Kelty has noted that while “conventional wisdom in both anthropology and history has it that what makes a study interesting, in part, is the work a researcher has put into gathering that which is not already available,” fieldwork among geeks and (bio)hackers often means working with subjects’ own “self-documenting history” of their work as they collect and archive it online (2008: 21).

In total, I conducted 53 formal semi-structured interviews, which lasted between one and four hours each. These interviews were conducted following protocols of open-ended questions I formulated in advance, but which I adjusted during interviews to allow for spontaneous turns in conversation. Whenever possible, I digitally recorded these interviews and transcribed them, either partially or in their entirety, using voice recognition software. If an interviewee preferred not to be recorded, I would take notes during the interview, either by hand or using word processing software. All of these interviews were conducted in person (except for one, which was conducted by telephone with someone I had already interviewed twice in person), and whenever possible, they were held privately (although in a few cases, interviewees preferred to meet in a more public venue, such as a lab or a café). All interviews were conducted in English, in which all interviewees were either proficient, fluent, or native speakers. Following grounded

theory, I analyzed transcriptions and fieldnotes by coding them according to both my own analytic concepts and those provided to me by my subjects (Charmaz 2006, Clarke 2005, Glaser and Strauss 1967). Subjects have given their approval for my reproduction of all quotations from interviews or private conversations.⁵ Unless noted otherwise, all the people named here are identified using their real names.

Scientific conferences are excellent places to gain a broad perspective on the international state of a research field. Although most of my fieldwork among synthetic biologists was based in Cambridge, I learned about other strains of synthetic biology by attending annual professional conferences in Zurich and Hong Kong. These conferences gave me access to research scientists whom I otherwise would not have been able to contact, allowed me to learn about research projects in a diverse range of academic and private research laboratories, and to become acquainted with research agendas that sometimes varied nationally (such as the French interest in synthetic biology as an engineering approach to theoretical biology). I also attended short (1 to 2 day) workshops devoted to topics in both synthetic biology and molecular gastronomy. In all of these places, I digitally recorded lectures and presentations and took fieldnotes both during and immediately after attending a lecture or speaking with an attendee.

Every few months, I would do a targeted search of online databases of academic journals and news aggregates to keep abreast of professional and popular written accounts of my fields of

⁵ Out of 53 interviews, I have included direct quotations from 15 subjects. Of those 15, 14 individuals gave me written permission to use their real names and to reproduce their words either as I had originally transcribed them or according to their modifications. I was unable to contact one subject before submitting this dissertation, and therefore have given her a pseudonym.

study. I would download and print as many articles as I reasonably could read, making selections based on the relevance of each article to my research agenda and the impact factor of the journal or news outlet in which the article appeared. I then would code these articles using the same system applied to my interview transcripts. This method was useful for learning how researchers presented their own work and how that work was depicted in public arenas. Nonetheless, because my work focuses on biological fabrication and sensation, my most potent research tool was participant-observation, as it allowed me to see how people work with biological things, gain skill through practice, and learn how to cultivate their senses in research contexts. Bringing my own sensorium to bear on this work, I suggest that “participant-sensation” is a more accurate way of describing my work of ethnographic sensing and making sense with my subjects.

MOLDING BIOLOGICAL SUBSTANCE: HISTORIES OF EXPERIMENTAL BIOLOGY

The story I tell draws upon a number of themes that have been ably addressed by anthropologists of biology, particularly those who have spilled ink figuring out how the category of “life” is something whose meaning is dependent upon, among other things, cultures, practices, institutional organizations, disciplinary contexts, national and local commitments, identity politics, property and funding regimes, historical moments, and all sorts of other things that can saturate such delicate epistemological tissue as that which we call “life.” What kinds of new biological things do biologists make in the service of understanding how biology works? In this dissertation, I argue that the people in each of my fieldsites are making an argument both about what biology is and how it may be understood: that biological substance may be understood

through its manufacture. In so doing, they explore the contours of “life” even as they remake it, either by pushing the limits of what counts as biology — rendering it partible, standardizable, audible — or by modeling it in abiotic media. Michel Foucault has claimed that “life itself” is a category that “did not exist” prior to the eighteenth century (1971: 139): “Life does not constitute an obvious threshold beyond which entirely new forms of knowledge are required. It is a category of classification, relative, like all the other categories, to the criteria one adopts” (ibid: 175). How is “life” tweaked, amended, and reformed by those who intervene into biological systems in order to apprehend “life” as a coherent object of inquiry? What I will claim is that constructive biologists, through their work crafting and sensing biology, destabilize life as a meaningful category of scientific investigation.

The current moment in biological inquiry is indebted to a long history of experimental manipulations of life in the service of life science research. Indeed, the history of biology is often narrated (by both biologists themselves and historians of biology) in terms of increasing human control over organisms, both by experimental and classificatory means and via genetic control of animal populations and heredities (Bud 1993, Derry 2003, Franklin 2007, Rabinow 1992). The mechanical physiologists of the French and British Enlightenments experimented on animals, imagining them as vital and well-designed machines to be measured and assessed (Guerrini 2003). Nineteenth-century physiological reductionists also manipulated living systems in order to determine and describe the internal forces regulating biotic systems (Coleman 1977, Coleman and Holmes 1988, Geison 1987, Holmes 1993, Mendelsohn 1974, Todes 2002). In France and Germany in the mid-nineteenth century, new measuring devices made it easier to

record physiological phenomena, which contributed to the reductionism of physiological experimentation by allowing experimenters to focus their attention exclusively on the physiological phenomena that were measurable and reducible to physical and chemical laws. They then extrapolated that all biological phenomena were similarly reducible.

Taking an interventionist approach to the increasing control over organisms to its logical end, the first groundswell of biological engineering was led by Jacques Loeb, a German-American biologist who sought to control life to the extent of developing a “technology of living substance” (Loeb 1890, quoted in Pauly 1990: 5). In *Controlling Life*, historian of biology Philip Pauly narrates the development of an engineering approach to the manipulation of biological materials among American biologists in the late nineteenth century. Loeb’s engineering ethos was marked by several characteristics: first, he argued that the distinction between “natural” and “pathological” biological structures or processes was irrelevant to the engineering of organic matter. For example, Loeb was most interested in the plasticity of living matter when working on artificial parthenogenesis, and was unconcerned by the fact that he was manipulating sea urchin reproduction in an artificial (“unnatural”) manner. Second, rather than believing that the goal of biology was fully to describe all living processes through experimental manipulation, he “reversed the priorities of analysis and control” (1987: 51). Analysis, for him, was merely a means to increase one’s control over biological matter. Third, he rejected the general theoretical questions of biology as overly philosophical, choosing to focus instead on direct intervention into biological processes. The entanglement of experiment and intervention and the analogy of bodies to machines enabled the development of a field committed to exploring the limits of

biological plasticity and to reengineering biological matter, a research agenda that remains central in the contemporary biosciences.

My work is beholden to the prodigious literature on histories of model laboratory organisms, which demonstrates that throughout the twentieth century, making new forms of life has been inextricable from the study of life. Karen Rader, in her institutional history of the standardization of Jackson Lab mice from 1900 to 1955, argues that such histories describe the relationship of “human and material agency” in biological experimentation (2004: 14). The first mouse houses, Rader reports, were funded by Detroit car factories, whose ethos of Taylorist production was soon adopted by Jackson laboratory breeders. The shift to mass production affected what characteristics were bred for in the mice. As I will show in Chapter 2, the Taylorist disposition remains alive and well in twenty-first century bioengineering. Angela Creager’s history of the tobacco mosaic virus demonstrates that biological change occurs incrementally and is based on material experimentation, emphasizing that laboratory tools and model organisms are mutually constitutive, developing only in interaction with one another (2002). So too in his history of fruit flies, Robert Kohler characterizes the genetics lab as an ecosystem in which *drosophila* and geneticists entered into a symbiotic relationship that changed the biology of *drosophila* and the course of genetics research (1994). Hannah Landecker narrates how in the twentieth century, cells, through their controlled growth and cultivation, became “living technologies” extricable from bodies. In the process, “life” was recast as malleable (2007).

The “made” biologies I interrogate in the coming chapters might be reasonably called “post-organismic,” in that they are no longer appraised as whole organisms. Synthetic biologists and biohackers treat biology as a series of partible functions that can be ported across organisms, sonocytologists are interested in the “vibratory world” at the heart of all metabolic systems, molecular gastronomers focus their attention on proteins, lipids, and nucleic acids as general biochemical classes, and women who craft the Hyperbolic Crochet Coral Reef are interested in hyperbolic geometry as a biological form common to multiple biological taxa and ecologies, from coral to kale. The “postvital” turn in twentieth century molecular biology meant the collapse of the body onto “a transparent sequence that has nothing behind or beyond it” (Doyle 1997: 13). Here, the post-organismic means that the biological features researchers fasten on are determined by their own experimental tactics, which they then identify with the thing itself. For example, techniques to make biology divisible mean biology is defined as inherently partible substance, and work to construct a cellular soundscape means biology, for these researchers, is inherently vibratory. Scientists build methods into substance, then interpret them as qualities already essential to biology (cf. Landecker, on tissue culture).

For anthropologists to make sense of how biologists and their confreres make sense of life, we must heed all of the sensory faculties by which they do so. Each of the fieldsites I consider in the following pages take a different tack in comprehending and engaging with the stuff of biology: synthetic biologists want to redesign it, DIY biologists want to “hack” it, sonocytologists use ultrahigh resolution tools to “touch” and “listen to” proteins, nucleic acids, organelles, and whole cells. The Hyperbolic Crochet Coral Reef project affirms the

entanglement of humans with other species, and seeks, in a manner akin to but different from earlier movements such as Artificial Life (Helmreich 1998), to recompose organic morphologies in different media, attending to the error-driven and processual nature of evolutionary change. Molecular gastronomers are also concerned with intimate forms of relating among entangled living things, but whereas sonocytologists project themselves into cellular landscapes, and crochet coral crafters speak to the shared environments of humans and hyperbolic marine organisms, molecular gastronomers are paying attention to the intimate (and intimately social) act of consumption: what biological substances we ingest, and how nature and culture, natural and artificial, can be recalibrated using the media of biochemistry.

Recent social studies of biology have appraised how institutional, political, and legal changes underwrite how biology is capitalized upon, how it ramifies in novel globalized economies, and how biological substance, actual and promised, comes to be value-laden (Cooper 2008, Fortun 2008, Franklin 2007, Rose 2007, Sunder Rajan 2006, Taylor et al. 1997). Other accounts examine how the instrumentalization of life — via cloning and genomics (Duster 2003, Franklin 2007, Goodman et al. 2003, Keller 2000, Rabinow 1999b, Reardon 2004, Thacker 2005), bioprospecting, bioinformatics, the circulation of biotic materials, and immortalized cell lines (Franklin et al. 2000, Hayden 2003, Helmreich 2009, Landecker 2007, Lock 2002, Waldby and Mitchell 2006), reproductive technologies (Davis-Floyd and Dumit 1998; Franklin 1997; Franklin and Ragoné 1998; Ginsburg and Rapp 1995; Hartouni 1997; Ragoné 1994; Strathern 1992a, 1992b; Thompson 2005) and “life” rendered in digital media (Helmreich 1998) — also remakes what Foucault called “life itself” (or, more multiply, “lives themselves” [Franklin and

Lock 2003] and “emergent forms of life” [Fischer 2003]) by altering biological plasticity, relatedness, propagation, form, and potential. Philosophical appraisals of biology discern that living substances act as rhetorical devices or softwares (Doyle 1997, 2003), or what I call in reference to synthetic biology, “persuasive objects,” that order both living things and “life.”

EXPERIMENTAL CULTURES, PRACTICES, AND EMBODIMENTS

Since the 1970s, social scientists and historians have approached scientific culture as a field of social practice like any other, amenable to the same tools of investigation and analysis as anthropologists apply to other cultural activities (Callon 1986; Collins 1985, 2004; Galison 1987, 1997; Knorr-Cetina 1981; Latour 1987; Latour and Woolgar 1986; Lynch 1993; Pickering 1984, 1995; Traweek 1988). The late-twentieth century turn to practice in the sociology of science and technology (Fujimura 1996, Lenoir 1988, Lynch 1985, Pickering 1992, Schaffer 1989) was undertaken by scholars who, in attending to everyday activities in laboratory and field sciences (e.g. the embodiment of “tacit knowledge” [Polanyi 1962]), called attention to what researchers of everyday life in laboratories and elsewhere came to call “craft” knowledge and practice.

Practice theorists have variously employed the terms “tacit knowledge” (Polanyi 1962), “making do” (Certeau 1984), “habitus” (Bourdieu 1977), “kludging” (Fortun and Bernstein 1998) and “doability” (Clarke and Fujimura 1992) to describe how practice becomes an engrained, unspoken, and embodied form of knowledge that is transmitted through face-to-face transactions. The “practice turn” in the sociology of science appropriated an understanding of craft facility as a goal-oriented refinement of physical skill to argue that “mastery of a practice cannot be gained from books or other inanimate sources, but can sometimes, though not always, be gained by

prolonged social interaction with members of the culture that embeds the practice” (Collins 2001: 107; see also Bloor 1991, Schatzki et al. 2001, Turner 1994). Practice, they claimed, is always “collective action” (Barnes 1992). The shift in emphasis from theory to practice in such work led to fresh thinking about the relation between theorizing, instrument building, and experimentation (e.g. Galison 1997). While in some cases, the craftspeople responsible for scientific instruments were the focus of discussion, particularly in connection with the rise of experimental ways of life (Shapin 1988), more often, early modern forms of artisanal work were used analogically to describe modern lab practices.

The attention contemporary science studies scholars pay to practice is influenced most clearly by the ethnomethodological sociology of the 1960s to 1980s. Ethnomethodologists, most famously Garfinkel, argued that “the objective reality of social facts” is an “ongoing accomplishment of the concerted activities of daily life” (1967: vii). Ethnomethodologists sought to examine how such daily activities are part of individuals’ making accountable of their behavior, by analyzing commonplace utterances, activities, and habits, and trying to discover the underlying formal properties of such activities. Sociologists of science applied ethnomethodological theory to scientific practice by doing fieldwork, following the everyday actions of scientists working in laboratories. Clarke and Fujimura refer to the conditions under which scientific tools are constructed as an “ecology of the conditions of its production — an ecology of scientific activity/practice/work” (1992: 5). Addressing how tools, jobs, and the rightness of tools for jobs are co-constructed by scientists, Clarke and Fujimura argue that tools are ad hoc constructions produced when scientists tinker to assemble the tools that are necessary

under given circumstances. Fujimura focuses on how tools change over time using the concept of “doability” — meaning how projects are organized so that they are feasible on several different scales that encompass material practice, larger institutions and fiscal responsibilities. She emphasizes that “rightness” is not predetermined, but is a result of scientific consensus and the work of constructing the tools (1992). Anthropologists and historians have noted that model making is a hands-on, interactive, dialogic, and skillful achievement that simultaneously brings new things and concepts into the world (Chadarevian and Hopwood 2004; Hesse 1963; Kingsland 1985; Klein 2003; Morgan and Morrison 1999).

Laboratory studies have emphasized that scientific practice is a heterogeneous, material, and processual activity that operates on different time scales and requires the social negotiation of fact production (Doing 2004; Galison 1987; Hacking 1983; Knorr-Cetina 1981, 1999; Knorr-Cetina and Mulkay 1983; Latour 1987; Latour and Woolgar 1986; Rheinberger 1997; Traweek 1988). Nonetheless, historically scientific discovery and craftwork have been deemed separate categories, as have experimentation and manufacture, and standardization and artisanship. Some science studies scholars (Bensaude-Vincent et al. 1996; Bleier 1986; Haraway 1989, 1997, 2007; Harding 1986, 1991; Hubbard 1990; Jacobus et al. 1990; Keller 1983, 1992, 1996 [1985]; Longino 1990; Rankin 2007; Tuana 1989) seek a feminist science in those technologies that have often been downgraded to the status of “arts” — most notably, the “arts” of animal husbandry and midwifery, which were later subsumed by technocratic science in the form of genetic breeding and obstetrics. Historian of biology Ruth Hubbard insists that a feminist science has always existed, but has not been recognized as such. She contrasts the places in which feminist

science has historically been conducted (namely, the home) to the laboratory, which has been the privileged space of science since the Enlightenment: “I am talking of the distinction between the laboratory and that other, quite differently structured, place of discovery and fact-making, the house-hold, where women use a different brand of botany, chemistry, and hygiene to work in our gardens, kitchens, nurseries, and sick rooms” (in Tuana, ed. 1989: 129). Scientific and artisanal identities — and the kinds of people and practices such identities imply — may alternately be sustained by or confronted with places tagged as appropriate for scientific or domestic production. The juxtaposition of scientific production with non-scientific space, and vice versa, transforms those performing scientific or artisanal labor, the objects of their production, and the spaces they inhabit, thereby also changing how “science” and “craft” are delineated. In this respect, this dissertation also identifies with histories of how the laboratory has been constructed as an epistemologically specific and circumscribed space (Chadarevian 1996, Gooday 2008, Klein 2008, Kohler 2002), which overlaps with my interest in atypical, illegitimate, or unrecognized modes of scientific inquiry, an issue that may go under the rubric of “popular science,” “public understanding of science,” or “amateur science.” In examining how sensory and craft biology remains a relevant and potent form of scientific activity, I ask how the modes of constructive biology I investigate are entangled with distinctions between knowledge and know-how, standardization and artisanship, scientific and artisanal workspaces, the commons and commoditization.

ANTHROPOLOGIES OF CRAFT PRACTICE

Ethnographic anthropology following the postcolonial, feminist, and reflexive critiques of the

1980s has increasingly included a dedicated focus on embodied modes of knowledge production and transmission. Many anthropologists today pay close attention to how culture conditions human bodies to be productive in disciplined, scripted, and unspoken ways (cf. Foucault 1976, 1977), but such work goes back at least to Marcel Mauss, who considered early on how bodies are produced by “techniques and work of collective and individual practical reason” (1935). Elaborating on Mauss, Pierre Bourdieu employed craft terms as metaphors to convey how bodies become fields of enculturation put into practice in everyday life, theorizing embodiment and bodily expression as skill, *savoir-faire*, dexterity, and *habitus*. Skill, for Bourdieu, was an effect of hegemonic and hierarchical structures reaching into bodies; craft techniques were examples of skill, but skill could be discerned across a wide range of bodily practices. Anthropologists’ attention to practice, borne, for some, of a convergence between Bourdieu’s *habitus* (1977) and Merleau-Ponty’s phenomenology (2002), produced a methodology Thomas Csordas described as “somatic modes of attention:” “culturally elaborated ways of attending to and with one’s body in surroundings that include the embodied presence of others” (1993: 138). This dissertation builds on the work of anthropologists of craft, and of practice more generally, who have articulated how “skill” is inculcated and attained among craft practitioners as an aspect of *habitus*.

For example, anthropologists have adopted Bourdieu’s theories to examine artisanship and craftwork as sites in which wider processes of enculturation and socialization may be observed, asking what studying craft and knowledge transfer among artisans can teach anthropologists about how social values, norms, and institutions are built into techniques of the body (cf. Lave and Wenger 1991). Dorrine Kondo, in studying Japanese confectioners, theorized

skill as “physical idioms of technical capability,” meaning that over years of training, skills become fixed in the body to the extent that they constitute artisan identity (Kondo 1990: 238) and demonstrated how, for the artisans she studied, making things strongly correlated with the crafting of selves (1990). By observing Cretan artisans, Michael Herzfeld (2003) extended Kondo’s analysis to suggest that the relations among things paralleled the maintenance of social relations, finding that the process of becoming an adept Cretan craftsperson entailed learning how to perform Greek masculinity. In her study of Italian family firms, Sylvia Yanagisako has shown how kinship, gender, and “sentiments” — that is, “emotional orientations and embodied dispositions” — can shape capitalist action (2002: 10). Anthropologists of craft also address how hegemonic structures are incorporated into artisans’ work and lives, as practitioners learn how to express their mastery in, for example, culturally specific, masculine idioms of hardship, performance, solidarity, and self-realization (Herzfeld 2003, Kondo 1990). Many craftspersons negotiate their work in the face of possible obsolescence or imposed perceptions of them as repositories of national identity or tradition (although such perceptions always admit room for creative resistance) (Terrio 2000).

By demonstrating how craft knowledges and social structures are embodied and performed, anthropologists of craft show that ways of thinking impact ways of doing and vice versa. I take this up on two levels in regards to constructive biologies: first, I examine how the work of making biological things generates new biological knowledge; second I track how these practitioners of biological making-and-knowing build into their artifacts culturally held notions

about moral economies of exchange and accreditation, folk theories of evolution, understandings of nature and artifice, and ideas about gender, heritage, and nation.

SENSORY ETHNOGRAPHIES

How are senses cultivated in particular contexts, bolstered and reconfigured by technical apparatuses, and through negotiation and discussion? More than something static, sensing is something that has to be agreed upon — what does it mean to *hear* something? Are you *really* touching an object or not? How is what can or cannot be discerned taste-wise cultivated? While these fieldsites are obviously not the only places to examine how the senses are negotiated in practice, science is a good place to start, because, first, so much laboratory furniture is devoted to extending, substituting for, amplifying or transducing our human senses, and second, experimental inquiry is one place in which what is true, artifactual, subjective, or objective gets sorted out on a daily basis. As such, sensory formations and their transformations can take center stage in the experimental life.

In figuring out how to write an account of biological experimentation and fabrication that attends to how people apprehend biology using their senses of taste, hearing, touch, and smell, in addition to vision, my work owes much to those anthropologists who have written multi-sensory ethnographies. While this literature has done much to critique the ocularcentrism endemic in anthropological and historical accounts of culture, it can sometimes fall prey to the sensory litany (see Sterne's audio-visual litany [2003]), an ideology that assumes that the dominance of one sense eclipses another, and that the senses bear fundamental characteristics (being directional,

perspectival, internal, external, subjective, objective, intellectual, affective, material, immaterial, essential, or superficial) apart from those bestowed on them by the people who are doing the sensing. By tracking how researchers build particular modes of sensing into biological objects, either by listening to cells, grasping material simulations of marine morphologies, or tasting the products of molecular gastronomy, I seek to appraise sensing as an active, local, and unstable negotiation that often is particular to the objects or environments being perceived, the means and techniques with which researchers amplify or extend their perceptions, and the meanings attached to particular sensory moments.

An important, emergent, and critical school of “sensory ethnographers” have argued that by relying solely on a fine-grained, but still objectivist, visual approach to ethnography, anthropologists often end up examining cultures only by literally “losing their senses,” and in so doing, overlook knowledge crystallized in sounds, tastes, smells, and textures (Fabian 2000, Stoller 1989). In response, anthropologists have increasingly included cross-cultural comparisons of the sensorium in their ethnographies (Desjarlais 2003; Geurts 2003; Howes 1991, 2005, 2009). In his ethnography of Nepalese Yolmo Buddhists, Robert Desjarlais claims, for example, that, “sensory perceptions are profoundly patterned by the technologies, social histories, and cultural sensibilities that contribute to people’s lives.... An anthropology of the senses thus calls for a study of the pragmatics of sensing as much it calls for a cultural analysis of sensory forms or a phenomenology of sensate experience” (2003: 341-2). Following Marcel Mauss (1935), we might ask how senses shape the “techniques of the body” whereby people fabricate new artifacts, and how people interact with such objects in ways that produce embodied

knowledge. In recent years, science studies scholars have increasingly turned their attention to the role of the senses in science and technology. While the literature is slim, what has been written demonstrates how important — and overdue — good analyses of the senses are to a critical social study of science (on science and sound, see Helmreich 2007, Mody 2005, Pinch and Bijsterveld 2004, Roosth 2009; on science and touch, see Gilman 1993, Herzig 2005, Myers 2006, Paterson 2007, Wilson 2004; on science and taste, see Paxson 2008, Roberts 1995; on science and smell, see Latour 2004).

This project offers a reading of what scientific work phenomenologically and sensorially entails. Scientific research, I claim, is not something done simply analytically, and scientific evidence is not only gathered visually. Paying attention to how scientific objects are appraised and evaluated using the senses of olfaction, tactility, taste, and audition will help uncover a significant aspect of scientific activity. Further, methodologically it will offer a new avenue of inquiry that has been under-examined by science studies scholars. Marx insists that “the forming of the five senses is a labor of the entire history of the world down to the present” (1968 [1844]: 139-141), and, further, that “the senses have therefore become theoreticians in their immediate praxis” (1992: 352). Horkheimer elaborates upon Marx’s claim to the historicity of the senses, writing that “Even the way they [‘men’] see and hear is inseparable from the social life-process as it has evolved over the millennia. The facts which our senses present to us are socially preformed in two ways: through the historical character of the object perceived and through the historical character of the perceiving organ” (quoted in Howes 2009: 15). It behooves science studies scholars, whose bread and butter is ferreting out how social practices crystallize “natural”

categories and kinds, to heed not only our discipline's own ocularcentrism, but also to reexamine the manner in which all of our senses have been "formed" over an "entire history," and, for that matter, continue to be *in formation*. Paying attention to how scientists listen to, taste, smell, or touch the objects of their investigation, and how these senses can direct and coordinate the kinds of questions scientists ask and the work that they do, could uncover an aspect of material and practice-based scientific inquiry that usually only figures tangentially in scientists' own accounts of the work they do.

OVERVIEW OF THE DISSERTATION

I have arranged this dissertation into six chapters, keyed to my five fieldsites plus a conclusion in which I ruminate on my own work as an ethnographer and on how the senses figure in anthropology. Although each of the main chapters in this dissertation describes and analyzes a single fieldsite, when read across one another they elucidate larger trends I think are diagnostic of the current moment in the life sciences.

Chapter 2. Synthetic Biology: "Life Is What We Make It"

This chapter reports on the Synthetic Biology Working Group, two laboratories at the Massachusetts Institute of Technology that were at the forefront of the burgeoning synthetic biology movement in the first years of the twenty-first century. Based on fieldwork among students in the lab of synthetic biologist Drew Endy, an increasingly public promoter of the field, I detail how synthetic biologists' claim that they are "constructing life" is rooted in MIT's long-standing hacker culture, such that biology is imagined to be another hackable substrate. The

connection to hacker culture is best exemplified by the story of Tom Knight, a famous hacker who in the early 1990s decided to turn his attention to engineering biology. I look at two recent projects in synthetic biology: one in which MIT graduate students worked to “streamline” and “rationalize” the genetic material of a bacteriophage virus, the other the work of Craig Venter to build a “synthetic” bacterium, and suggest that these projects demonstrate how made biological things function as “persuasive objects” that destabilize the category of “life.” Relying on anthropologists of craft who have argued that artisanal personae materialize in the process of learning how to master a craft, I argue that through the work of making and assembling standardized biotic parts that are freely shared within the synthetic biology community, synthetic biologists also forward-engineer themselves as a community dedicated to Open Source approaches to biological manufacture. Further, I inspect the catalog of standardized biological parts, or BioBricks, in which I discern a new taxonomy in which transgenic exchanges underwrite social exchanges: in unmooring biological substance from “source” species, synthetic biologists promise a free circulation of value-laden biotic artifacts putatively outside of intellectual property regimes. Genetic and social sorts of circulation and relatedness remake and reflect one another in moral economies of bioengineering.

Chapter 3. DIY Biology: Life Makes Itself at Home

This chapter tracks the circulation of made biological parts *outside* of the synthetic biology labs in which they were manufactured and into the homes and community-organized hacker workspaces” in which young, college-educated, middle-class Americans use standardized biological parts to pursue amateur biological engineering projects. Reporting on the amateur

organization of biohackers, a group started in Cambridge in 2008, I ask why such a movement has manifested itself alongside synthetic biology. I argue that in both synthetic biology and DIY biology, fabricated biological things (e.g., BioBricks) are both made by and constitutive of social assemblages dedicated to building, modifying, and exchanging these genetic parts. If synthetic biology is an imagining of the substantive matter of biology as it could be, then DIY biology is an imagining of biology, the discipline, as it could be, or rather as it could be *undisciplined*.

Drawing on ethnographic data and material gleaned from the online forum for amateur biologists, and telling the story of one biohacker, a young woman named Kay, who conducts genetic tests on herself in her bedroom closet, I argue that practitioners do hobbyist biology research in order to refuse the articulations of knowing and making, analysis and synthesis, induction and production, endemic in biology and bioengineering disciplines. They approach biology as process rather than product and use biological practice as a mode of political speech arguing for the right to do biological experimentation and engineering.

Chapter 4. The Hyperbolic Crochet Coral Reef: Evolutionary Yarns in Seahorse Valley

The Hyperbolic Crochet Coral Reef is a distributed venture of thousands of women who are cooperatively fabricating a series of yarn and plastic coral reefs in order to draw attention to the menace climate change poses to the Great Barrier and other reefs. The project first took shape when Margaret Wertheim, a science writer, discerned that mathematical models crocheted by geometer Daina Taimina evoked the morphologies of the organisms of the Great Barrier Reef. This chapter is an ethnographic dispatch on the Reef and those engaged in making it, based on interviews with Reef makers and observations in workshops teaching women how to crochet

these biological forms. I interpret the Hyperbolic Crochet Coral Reef as a single instance of “constructive biology,” which I construe as being about hooking together knowing and making. For the makers of the Reef, fabrication is more than simply materializing metaphors or rearranging configurations of things; it is a mode of improvisational and exploratory, materially engaged craftwork, a constructive grappling with biological things apprehended via their manufacture. I claim that a new sort of engagement with biology may be in the making for Reef contributors, one that, like the sort of biology espoused by the biohackers in Chapter 3, is about apprehending biological form not just materially, but processually. I show that one consequence of such a process-oriented grasp of biology is that Reef contributors draw on both theoretical biology and folk theories of evolution to construe biology as itself a process of bringing-into-being (specifically, an evolutionary one) that, like crafting, tends to be changeable, error-prone, messy, and at risk. Further, manufacturing such forms renders biology something whose evolutionary unfoldings crafters not only mimic, but also analogically generate, through an ad hoc crafting of new crochet forms. The function I identify in hyperbolic crochet is located in both the crafted product and the crafted gesture, in the act of crocheting performed by Reef makers: it is the time-intensive physical labor put into crocheting and the improvisational experimental work of generating new forms that offers an embodied understanding of biological form and the temporality of evolutionary generation.

**Chapter 5. Screaming Yeast:
Sonocytology, Cytoplasmic Milieus, & Cellular Subjectivities**

Sonocytology, a technique in nanotechnology research, uses a scanning probe microscope to record the vibrations of cell walls, amplifying those vibrations so that humans can hear them.

Yeast cells vibrate approximately one thousand times per second, and most cells vibrate within the frequency — though not amplitude — range of human hearing. In this chapter, I address how cellular vibrations are converted into sounds that scientists can interpret as conveying meaningful information regarding the dynamism of cellular interiors.⁶ Drawing on published materials in both scientific journals and the popular press, and supplementing that material with an ethnographic account of working in the Gimzewski lab at UCLA, where sonocytology was developed, I examine the conditions that enable scientists to describe cells as actors capable of “speaking” or “screaming,” and how listening to cellular sounds may eventually change how scientists think about cells — as subjects that are dynamic, environmentally situated, and experiential. While subjectivity implies the ability to speak to one’s conditions, it also suggests that actors’ utterances are conditioned by epistemic and ideological regimes. The technique of sonocytology I here describe produces an ambiguity between cells speaking and cells being spoken *for*. The primary question I here address is how raw *sound* is transformed into *signal* — that is, how scientists convert inchoate cellular vibrations into meaningful scientific data. The sonification of cells, I argue, requires lab personnel to become skilled in apprehending (looking at, listening to, and touching) subcellular landscapes and constructing soundscapes through apprenticeships in building, refurbishing, and wielding bespoke microscopes. I first describe the history of sonocytology and the microscopes used to listen to and touch cells, then focus on three epistemological effects of using sound scientifically to explore otherwise inaccessible spaces: the first concerns the ways we think about organisms in their environment and in relation to other organisms, the second bears on the question of how we think about the insides of organisms as

⁶ A version of this chapter was published as an article in *Critical Inquiry*. See Roosth 2009.

stages on which dynamic biological processes are performed, and the third asks how listening affects — and also effects — our own tactile and embodied contact with these entities.

Chapter 6. Molecular Gastronomy: From the Life Sciences to the “Science of Everyday Life”

This chapter functions as a rhetorical relay between previous chapters and my conclusion. In it, I describe a food movement called “molecular gastronomy,” which practitioners — physical chemists and biochemists who study food, and chefs who apply their results — broadly define as the application of the natural sciences and laboratory apparatuses to furthering cooking and the culinary arts. While in previous chapters I trace how biology is currently being remade, this chapter explores what in turn a remade biology makes, asking how crafted biologies reshape other domains of action. I describe the Paris laboratory of Hervé This (a physical chemist and French scientific celebrity) in which I did fieldwork and recount the history of molecular gastronomy, then turn to key aspects of constructive biology as they are manifested in molecular gastronomy. I pay special attention to how narratives of heritage and progress remake French culinary pasts and futures and I address how molecular gastronomers denigrate gendered practical knowledges as “old wives’ tales,” seeking to formalize those customary practices that are laboratory-tested to “work” and to recast cooking as secondary to verifiable scientific knowledge about food and cooking. In examining how “old wives’ tales” warrant and motivate molecular gastronomy research, I unpack how molecular gastronomers think about “culture” in an anthropological language indebted to French structuralism. If the importation of craft practices into scientific fields is, as I argue in earlier chapters, a means of remaking things biotic, the importation of scientific practice into cooking remakes “culture,” or a particular notion of

Chapter 1: Introduction

culture, such that it is always an object of scientific remediation and recapture, re-entrenching social kinds like nation, gender, and class. I close by arguing that *taste*, as both somatic sensation and cultured discernment, is being molecularized, fostering new sensorial imaginations of biochemical forms and events.

Chapter 7. Conclusion. Sixth Sense: The Anthropologist as Sensor

Having examined the status of senses in current biology, bioengineering, and allied life science practices, I conclude this dissertation by reflecting on how ethnographers might draw upon and metabolize their own thickly sensate experiences in the field to do anthropology otherwise. Thinking about my own practice alongside that of my interlocutors — synthetic biologists, biohackers, hyperbolic crocheters, sonocytologists, and molecular gastronomers — opens up a series of questions about the ocularcentrism and perspectivalism of ethnographic research and writing. Taking a page from my subjects, I aim to recast my own ethnographic practice as an engaged and embodied apprenticeship in learning how to skillfully sense and *make sense* of technoscientific cultures.

Chapter 1: Introduction

Chapter 2. Synthetic Biology: “Life Is What We Make It”¹

CONSTRUCTIVE BIOLOGY (TM)

In fall 2006, I sat in my usual spot at the back of the reading room on the fifth floor of the old Koch biology building at the Massachusetts Institute of Technology. Unlike other MIT biology labs whose meetings I had attended, the Endy meetings had a convivial and lively air — we would snack on popsicles and candy, a defunct centrifuge in the lab’s rec room was well-stocked with bottles of beer, and lab meetings would sometimes adjourn to parties. Chalk it up to disciplinary dispositions: at the time, Drew Endy’s lab was at the forefront of “synthetic biology,” a new movement in bioengineering that grew up at MIT at the turn of the twenty-first century. The group’s aim: to turn the stuff of biology into an engineering platform, then freely share it.²

¹ The cover of a special issue of *Nature* devoted to synthetic biology (November 2005) bore the byline “Life is What We Make It.”

²The current use of the term “synthetic biology” to refer to the manufacture of complex biological systems from standard biological parts, as opposed to earlier uses of the term by artificial life scientists in the 1990s (Helmreich 1998) or French biophysicist Stephane Leduc in 1912 (Keller 2002), dates from the late 1990s, when practitioners used the term to designate a project they envisioned as “modular cell biology” (Hartwell et al. 1999). In its most simple articulation, there is really nothing particularly *new* about synthetic biology. Indeed, the twentieth century alone is littered with synthetic biology’s antecedents. Jacques Loeb proclaimed in 1911 that, “we must either succeed in producing living matter artificially, or we must find the reasons why this is impossible” (quoted in Keller 2002: 18). Loeb’s pronouncement, in which knowing and making are indissoluble, could have been uttered by any synthetic biology booster for whom viable synthetic systems are crucibles in which to try the accumulated store of knowledge experimental biology produced in the last century. The primary difference is that while the 1910s and 1990s editions of synthetic biology sought to materialize biological forms *beyond* organic media, in crystals and computer programs, the most recent iteration of the field works in wetware, but redesigns it according to the principles of mechanical and electrical engineering: biology either built up, like Legos, or booted up, like a computer.

As a professor in the Department of Biology and Biological Engineering at MIT, Endy helped develop the Registry of Standard Biological Parts, which stored and circulated “standardized” genetic materials (or, as MIT synthetic biologist Tom Knight named them, “BioBricks”). BioBricks are genetic coding sequences that adhere to synthetic biology community-defined composition standards. They are stored both digitally in an online catalog and physically in freezers at MIT’s Registry of Standard Biological Parts. As I will argue, synthetic biologists are the sole users of BioBricks, and their manufacture and distribution constitutes a “moral economy” (Kohler 1994) of researchers dedicated to building, modifying, and exchanging these parts. Synthetic biologists’ hackerly stance towards bioengineering is underwritten by BioBrick parts’ putative modularity, as practitioners value collaboration and sharing and posit that standardizing genetic components will engender “openness.” These parts are at once technical objects and social tools that orient and organize the synthetic biology community.

While at MIT, Endy also co-founded and directed the BioBricks Foundation,³ which saw to the legal status of BioBricks. He organized the first International Genetically Engineered Machine (iGEM) competition, which teaches undergraduates how to work with and build BioBricks, and publicizes the use of these Open Source parts. Founding a synthetic biology start-up company to synthesize more BioBricks, Endy increasingly became the figurehead and media darling of synthetic biology. As Endy’s star rose, both his doctoral students and synthetic biology skeptics portrayed him as a charismatic and “larger than life” “religious figure.” For

³ The BioBricks Foundation is a not-for-profit foundation founded in 2005 by professors at MIT, Harvard, and the University of California San Francisco.

members of his lab, casting themselves as firebrands and biological subversives meant disposing of the formalities of academic biological research. They dressed down, cracked jokes, interrupted one another. They believed they were on the cusp of something really important, and their enthusiasm was infectious.

Imagine my surprise, then, when things sometimes turned formal, even icy. On one Wednesday evening, a first-year graduate student in Computational and Systems Biology, during his first presentation to the lab, made the unfortunate mistake of beginning a sentence: “What Drew [Endy] did after he created this [bacteriophage]...” The room, which moments earlier had been abuzz with questions, side conversations, and laughter, fell silent. Endy spoke first, in careful and measured tones. “We don’t *create* biology, we *construct* it.” The student turned successive shades of red, stammering after Endy, “umm, right, right, *constructed*.” I was sympathetic, having stumbled a few months earlier into a similar semantic snafu in an email exchange with Reshma Shetty, another graduate student in the Synthetic Biology Working Group. After attending an undergraduate bioengineering lab for which Shetty was a teaching assistant, I had emailed her to check my understanding of the biology behind the lab protocol. In my email, I wrote, “The enzymatic activity of beta galactosidase creates the pigment in those cells not exposed to light.” In her response, Shetty remarked, “We like to avoid using the word ‘create’ in synthetic biology because of its god-like connotations and because it is not scientifically accurate. I would say that beta-galactosidase *generates* the pigment from a substrate instead of *creates*” (Personal Communication, April 18, 2006, emphasis added).

Why was it so important to synthetic biologists to characterize what they were up to as “constructing” rather than “creating”? The first answer is both the most obvious and least satisfying: around 2006, synthetic biology started coming under fire — from the popular press, citizen action groups, and other scientists — who accused synthetic biologists of wanting to “play God.” The verb “create” turned inflammatory, even as it added to the field’s hype by suggesting that synthetic biology could be powerful enough to give God a run for his money. But I think the creation/construction junction reveals something more fundamental about synthetic biology: it is a “constructive biology,” by which I mean that it is a field, similar to others in this dissertation, in which practitioners believe that understanding how biology works is best advanced by making new biological things. It was in listening to how synthetic biologists talk about “constructing” that I first started thinking about these new approaches to biology as “constructive,” as the phrase triggered two insights. First, it is a description of the way I see biology being made and remade in multiple fields. It also offered an intriguing resonance with science studies literatures on the “social construction of X.”⁴ The Science Wars had, after all, been waged over the contested construction of scientific facts (Hacking 1999, Nelkin 1996, Traweek 1996); and here were scientists making both material and ontological constructions of “life,” and admitting — insisting! — that they were indeed constructing things.

⁴ Where X = “technological systems” (Bijker, Hughes, and Pinch 1989), “what?” (Hacking 1999), “scientific facts” (Latour and Woolgar 1986), “scientific knowledge” (Mackenzie 1981, Myers 1990), “scientific controversy” (Altimore 1982), “extraordinary science” (Collins and Pinch 1982), “housework” (Bose, Bereano, and Malloy 1984), “biology articles” (Myers 1985), “validity” (Bowden 1985), “artefacts” (Elzen 1986, Russell 1986), “facts and artefacts” (Pinch and Bijker 1984), “learning in planarian worms” (Travis 1981), “mountain bikes” (Rosen 1993), “invention” (Cooper 1991), “the automobile” (Kline and Pinch 1996), “the Landsat satellite system” (Mack 1992), not to mention race, gender, illness, nature, knowledge, reality, and much, much more.

Obviously, “social construction” is a metaphor. Nonetheless, following the backlash against social constructivism of the 1980s, Ian Hacking suggested that:

If we are to return ‘construction’ to life, we should attend to its ordinary meanings, as in constructing a five-string banjo. The core idea, from the Latin to the present, is that of building, of putting together. The fairly new (1992) *American Heritage Dictionary* first offers, ‘to form by assembling or combining parts’.... Constructionalists and constructivists are true to the root metaphor of construction as building. Let us now urge constructionists to keep the same faith. Anything worth calling a construction has a history. But not just any history. It has to be a history of building (1999: 49-50).

Building and putting together. In this respect, Hacking, synthetic biologists, and biohackers (as we will later see) are in agreement. However, while synthetic biologists assert that they are building biological things, I claim that they are also bringing “life” under construction and that their constructive work also makes new socialities. In putting together biological things, they are also putting together communities of exchange and practice. Central to Ian Hacking’s formulation of social construction is that putting together things, concepts, and people are fundamentally different types of construction to be appraised separately. Diverging from this interpretation, I focus my analysis on how biological things, theories of “life,” and synthetic biologists all forward-engineer one another. My understanding of constructive biologies is thus indebted to Sheila Jasanoff’s notion of co-production, which she explains is “not about ideas alone; it is equally about concrete, physical things. It is not only about how people organize or express themselves, but also about what they value and how they assume responsibility for their inventions” (Jasanoff, ed. 2004: 6). She identifies at least four sites of co-production: “making *identities*, making *institutions*, making *discourses* and making *representations*” (ibid: 38).

Codon Devices, a DNA synthesis company started by Drew Endy and George Church, a Harvard systems biology professor, trademarked the phrases “constructive biology” and “the constructive biology company,” printing them on glossy advertisements in conference programs, often accompanied by an image of a nucleic construction site, cranes lowering codons



Figure 2.1. “Constructive Biology (TM):” Advertisement for Codon Devices.

(sequences of three nucleotides) onto towering spires of double helices [Figure 2.1].⁵ Such images suggest that construction, for synthetic biologists, means life is “under construction,” a work in progress. Also under construction, I claim, is a new kind of biological researcher: *practitioners simultaneously assemble the biological and the social, and do so in ways that they build into their objects.*

This chapter is based on fieldwork I conducted among synthetic biologists from 2005 to 2009. I attended weekly laboratory meetings of the MIT Synthetic Biology Working Group, smaller group meetings devoted to specific research and publishing issues, annual professional conferences and frequent public lectures, and met informally with members of the laboratory. I spoke with numerous synthetic biologists, and formally interviewed many of them. I took graduate courses in MIT’s Department of Biological Engineering and observed undergraduate laboratories in the same department. I participated in MIT’s Synthetic Genomics Initiative, which was organized around discussions of the “social” and ethical implications of synthetic

⁵ The trademark that suffixes “constructive biology (TM)” reminds me that living things, in the era of biotech, are now ordered according to “brand” rather than “kind” (Haraway 1997). As I will claim later, taxonomies of synthetic biology objects now reflect the social relations by which parts circulate as much as they reference source species. *Brand* merges with *kind*. Codon’s trademark lapsed when the company shut its doors in April 2009, so I here use it with abandon without fear of actionable infringement.

genomics.⁶ Reading articles in scientific journals, I struggled, through reading and conversation, to learn the language spoken by synthetic biologists. I tracked down mentions of synthetic biology in the popular press, noting each year how much harder it was becoming to stay abreast of that literature as synthetic biology mushroomed from a minor movement centered at MIT into a more conspicuous phenomenon, which even garnered the attention of other anthropologists, historians, philosophers, sociologists, and legal scholars of the sciences (Keller 2009; Lentzos 2009; Mackenzie 2010; O'Malley 2009; Pottage 2006; Rabinow 2008, 2009).

I here pursue two claims: first, that the things synthetic biologists make function as *persuasive objects* — that is, making life is not necessarily an end in itself, but also a technique with which to probe life's margins. In making new biological artifacts, synthetic biologists explore life's limits: what constitutes a “minimal” organism? How can living entities be streamlined? Can an organism be made entirely synthetically? What might the “first” organism have looked like? Can the functions of genetic material be standardized? Assembled things materialize these questions, but also signify their answers. While this first argument addresses the relation of biological things to theories about life, the second attends to the relation of these

⁶ Synthetic biologists have devoted much attention to the “social” implications of synthetic biology, even dedicating a full day of their second annual meeting to what they described as synthetic biology's “Asilomar.” The NSF Synthetic Biology Engineering Research Center (SynBERC), includes one “thrust” devoted to “human practices.” In meetings on “social implications” of synthetic biology, professors and grad students often claimed that the success of synthetic biology relied on “educating” the public, assuming that if “the public” simply understood enough science, it would find no fault with biological engineering. As Craig Venter phrased it in the *New Perspectives Quarterly*, “the biggest problem with respect to cloning is that the public gets its science education from Woody Allen and Arnold Schwarzenegger movies” (2005). For example, I heard synthetic biologists deride “the public” for opposing genetically modified foods or, closer to home, Boston University's Biosafety Level 4 laboratory. Some social scientists have patted synthetic biologists on the back for having “shown unusual leadership in early and proactive identification of some of the social, environmental, ethical and security concerns raised by the technology” (Lentzos 2009: 304). Synthetic biologists' continued concern for “the public,” I would suggest, is in accord with Marilyn Strathern's claim that “science incorporates society into its aims and objectives in order to preempt society's verdict” (Strathern 2004: 10). It also is another example of how synthetic biologists are working to forward-engineer their community, which necessitates priming the political and media landscapes that will adjudicate the ethicality and safety of their work.

things to biotechnical socialities. Nonetheless, the two claims are linked: these biological artifacts persuade synthetic biologists that life is partible, abstractable, and standardizable, a stance that allows them to cultivate hackerly identities and communities of practice around manipulating and exchanging biological things. Making more synthetic biologists and making standardized biological parts are inseparable agendas for synthetic biologists: the work of making standard biological parts, which are freely shared (both as sequence and physical matter) through the Registry of Standard Biological Parts, defines who counts as a synthetic biologist, and is even the entrance ticket into the community. Synthetic biologists embed the technical and practical norms (of synthesizing, assembling, modifying, and sharing) they want to ground their movement in the objects that they make. In engineering BioBrick parts, they seek also to forward-engineer a community dedicated to Open Source approaches to biological engineering.

In the first part of this chapter, I report on some of the engineering principles and rhetorics that animate synthetic biology, then describe synthetic biologists' attempts to explore biology and remake the contours of what counts as life via its construction. This approach, which synthetic biologists call "bottom-up," is currently the most conspicuous research agenda in synthetic biology, as researchers work to build new forms of life "from scratch." It is also the clearest example of what I consider constructive biology's essential precept: that in making new biological things, the contours of "life" as an object of investigation and fabrication are also under construction.

I next tell a story about how synthetic biology (or at least its MIT strain) came to be. This story, about how hackers and electrical engineers first started thinking about life as an engineering substrate, and how hackerly dispositions subsequently were built into this emergent movement of biological engineering, will ground my second claim. I turn to MIT synthetic biologists' efforts to designate and standardize Open Source biological parts, and to encourage the circulation of those parts, showing how applying standards to biological things is used to beget openness, how transgenic, post-organismic menageries of biological devices knit together both species and socialities, and how a moral order (for both individual and collective action) gets written into biological things.

SYNTHETIC BIOLOGISTS AT MIT, 2004-2008: BIOLOGY, OUTSOURCED

The term “synthetic biology,” as Evelyn Fox Keller has suggested, is ambiguous, as “synthetic” can refer either to something constructed or something artificial (Keller 2009). Biology here is also an ambiguous term, as it might refer to either biological material or the discipline of biology. Synthetic biology, *the disciplinary object*, points us to the fact that the aim of the field is to manufacture forms of life not previously found in nature, that is, *synthetic* in the sense of an entirely new entity. Synthetic biology, *the discipline*, points us to the fact that the field is a hodgepodge of science and engineering that has attracted mathematicians, computer scientists, electrical engineers, biologists, and biochemists. “Synthetic” here means an alloy of existing parts (or, as Peter Galison calls such disciplinary syntheses, a “trading zone” [1997]). Keller has pointed out that synthetic biology straddles science and engineering, and that it even denies “any meaningful distinction” between the two. What interests her, she writes, is “the repeated

assertion that making is knowing, that the building of a machine is not only of obvious practical utility, but that that process is also, in itself, the royal route to an understanding of the machine. Making is knowing, and knowing is making” (*ibid*). What is at stake in synthetic biology is a confluence of the Aristotelian categories of *episteme* and *techne*, of knowing that and knowing how.

Synthetic biology is also ambiguous in more routine ways: synthetic biologists do not agree on who is a synthetic biologist. A 2009 news feature in *Nature Biotechnology* asked 20 prominent synthetic biologists to define synthetic biology. Their answers varied so widely that the journalist griped, “Similar to other new and trendy fields, synthetic biology has been defined so loosely that it can seem like all things to all people. Traditional genetic or metabolic engineering has been rebranded as synthetic biology, often to take advantage of the hype cycle that fuels investor interest” (Anon 2009b: 1071).⁷ Because it is a social movement that seeks to enroll new members from across the sciences, a little bit of definitional instability is written into synthetic biology’s charter from the get-go: synthetic biologists want to make or recruit more synthetic biologists, and as funding for synthetic biology continues to flow, many researchers are happy to identify their work as synthetic biology. As Kristala Prather, an MIT synthetic

⁷ This definitional ambiguity was apparent in a journal club I attended, which was meant to introduce undergraduate and graduate students to the current state of the field. Many of the papers we read were written by people who would probably not affiliate themselves or their projects with synthetic biology, even papers published long before synthetic biology got started (e.g., Bushman and Ptashne 1988; Savageau 1977). Topics addressed in papers included: computational design algorithms to redesign binding specificities of receptors in proteins (Looger et al. 2003), conversion of transcription repressors to promoters with the addition of an activating patch, how to combine rational design with directed evolution to “debug” and “fine-tune” synthetic networks that behave “unpredictably” due to “highly context-dependent” behavior (Yokobayashi et al. 2002), the manufacture of hybrid proteins that combine *E. coli* repressor proteins with yeast transcriptional activators (Brent and Ptashne 1985), the manufacture of *in vivo* bacterial “binary logical circuits” by combining genes for transcriptional regulators and promoters (Guet et al. 2002), and technical developments such as using assembly PCR to synthesize long DNA sequences out of large numbers of oligonucleotides (Stemmer et al. 1995).

biologist, put it, “If you ask five people to define synthetic biology, you will get six answers” (ibid: 1073). Modifying the recursive definition of hacker identity, with which synthetic biology significantly overlaps, one might claim that, “You are a synthetic biologist when another synthetic biologist calls you a synthetic biologist” (cf. Kelty 2008: 36, on “hackers”).

Enabled by three decades of technical breakthroughs in genetic engineering and DNA synthesis,⁸ the prevalence of computational metaphors for things biotic, which were ported into biology from linguistics and information sciences in the 1940s and 50s (Kay 2000) and proliferated in the wake of post-Genome Project research agendas like bioinformatics and systems biology, changes in the intellectual property regimes and governance of manufactured

⁸ The two technological breakthroughs most often identified with genetic engineering are recombinant DNA and the polymerase chain reaction (PCR), the first a technique Stanley Cohen and Herbert Boyer developed in 1972-3 to construct hybrid DNAs from naturally existing sequences in multiple species, and the second a means of amplifying a segment of DNA, developed in 1983-1984. The development of recombinant DNA technology was described by a journalist from *Rolling Stone*, one of the sixteen non-scientists allowed to attend the 1975 Asilomar conference, as “the discovery of the first rudiments of grammar for that previously unspeakable genetic tongue” (Rogers 1975: 37), a means of stitching together DNA segments from distinct species to construct chimerical organisms in the laboratory. Following on recombinant DNA’s heels by a decade, scientists working for the Cetus Corporation developed the polymerase chain reaction, a clever exploitation of DNA’s capacity to polymerize to replicate segments of DNA (Rabinow 1996).

organisms,⁹ the use of digital databases to catalogue genomes, proteomes, and other -omes, and a glut of federal funding for the biological sciences in the 1990s and the early years of the 21st century, synthetic biology seeks to merge biology with engineering, and experimental research with manufacture. While the most visible proponents of synthetic biology insist that the field is global, going so far as to locate the 2008 synthetic biology conference in Hong Kong in order to prove the point, the vast majority of synthetic biology research occurs in Western Europe and the United States. Of that work, much is concentrated in California and New England, and in Cambridge, Massachusetts in particular. By 2008, when I wrapped up my fieldwork, the synthetic biology research market had swelled to 600 million dollars, and an estimated 95 American universities were doing some kind of synthetic biology research (Bernauer 2005). This research was funded primarily by the National Institutes of Health, the Defense Advanced Research Projects Agency (DARPA), the Department of Energy, and the National Science Foundation, as well as by private organizations, universities and venture capital

⁹ Social inquiries into the governance of new biotechnical capacities to cut, copy, and paste genetic material, including the Gordon Conference in 1973, the Asilomar Conference in 1975, and the NIH-issued guidelines for working with rDNA [1976] underlined the fact that while these technologies and the new biotechnical entities they engendered may be laboratory-born, they shared a biology with the many organisms living beyond laboratory doors, who therefore maintained a very real stake in their production, containment, and potential dispersal. Synthetic biologists continue to grapple with the repercussions of these debates as they work to present their own community as capable of self-regulation. Asilomar was fundamentally an attempt by the biology community “to avoid public interference and to demonstrate that scientists on their own could protect laboratory workers, the public, and the environment” by evaluating the medical and environmental risks recombinant DNA technology posed (Weiner 2000: 910). The following year, the city council of Cambridge, Massachusetts questioned scientists from MIT and Harvard about whether the safety guidelines developed by the NIH in the wake of Asilomar would satisfactorily ensure the health and safety of Cambridge citizens, and placed a temporary moratorium on all recombinant DNA research on both campuses until the matter could be reviewed more fully by a board of citizens (Weiner 1979, 2000, 2001). Other legal and legislative decisions furthered genetic engineering in the 1980s and 90s by designating engineered organisms as the result of human art and therefore patentable, alienable, and commodifiable (*Diamond v. Chakrabarty* in 1980; *Moore v. The Board of Regents of the University of California* in 1990) (Jasanoff 1997, 2005; Landecker 2008).

(Bhutkar 2005).¹⁰ Such organizations, which fund the lion's share of professional synthetic biology research, are interested in the field primarily for its potential commercial applications, such as clean energy, cheap drug synthesis, and bioweapons (Andrianantoandro 2006, Church 2005, Forster and Church 2007, Purnick 2009). Though its skeptics and detractors claim synthetic biology to be empty hype, that hype quickly attracted extravagant financial support.

Much synthetic biology research is described as either “top-down” or “bottom-up” bioengineering (Peretó and Català 2007), where projects such as Craig Venter's efforts to build a synthetic “minimal” microbe count as “top-down,” and Drew Endy and Tom Knight's BioBrick parts count as “bottom-up.” In practice, many of these projects combine the two approaches, first trimming nonessential genetic sequences and then synthesizing these simplified systems. The most prominent — and mediagenic — example of recent synthetic biology work is Jay Keasling's development of a synthetic microbial pathway cheaply to synthesize artemisinin, an anti-malarial compound, for distribution in developing countries (Martin et al. 2003, Ro et al. 2006). Bottom-up projects advance the claim that biotic substance can behave mechanically by manufacturing ersatz mechanical devices out of genetic components and cells: clocks (Elowitz et

¹⁰ In 2005, representatives from DARPA approached Endy, saying that the government wanted to either classify all synthetic biology research or suspend funding; the National Science Foundation and the Department of Energy wanted to change the field's name, which they considered politically incendiary, as a condition of their funding. The office of the directors at the Department of Energy were forced to accept the field's name when it was printed on the cover of *Nature* in November of 2005, above the byline, “Life is What We Make It.”

al. 2004) and cameras (Levskaya et al. 2005) are foremost among these projects.¹¹ Such projects further the equation of genetic material to electronic components, as manufactureres compare the biological elements that make up these systems to “transistors,” “capacitors,” and other bits of circuitry.

Allow me to zoom in from this bird’s-eye view of the field to describe what synthetic biology looked like when surveyed from my ethnographic perch at MIT. From my regular seat in lab meetings, I could see the door to the Endy laboratory down the hall, which was shut while everyone was assembled during weekly group meetings. Two signs were affixed to the lab’s door: one read “tools of mass construction,” the other announced that synthetic biology was the “*real* intelligent design.” In 2005 and 2006, the country was knee-deep in George W. Bush’s second term, and the two signs reminded me of the political atmosphere in which the people surrounding me in the reading room were trying to rear a new scientific field. By 2006, the U.S. had already abandoned its search for weapons of mass destruction in Iraq, and Bush had publicly advocated teaching intelligent design in school science curricula. These were unsettling times for biology, especially in the U.S., where scientific expertise was definitely no longer what it used to be, and where the sorts of things made in university biology labs were cause for public and

¹¹ Lecturing to MIT undergraduates, Drew Endy repeatedly used the term “primitive” in describing such artifacts: synthetic biologists had made a “primitive clock” and a “primitive photography system,” undergraduate teams participating in the International Genetically Engineered Machines competition (iGEM) were able to make “primitive balloons” in gas bladders within bacteria, the MIT iGEM team had recently made bacteria smell like bananas using a “primitive computer program.” The use of the word “primitive” is at once an apologia and a placeholder promising things to come: if clocks and cameras are primitive now, it is only in reference to the biological clocks and cameras that, by implication, are soon to be built. Coding something as “primitive” assumes its eventual refinement (for an analysis of how “primitivizing” language worked similarly among Artificial Life scientists, see Helmreich 1998). Harvard synthetic biologist George Church extended primitivity from biotic artifacts to synthetic biologists themselves, saying in a lecture in Cambridge, Massachusetts that, “It’s like we’re in the ‘50s in the sense that we’re just beginning to get comfortable with our parts the way in the ‘50s they were getting comfortable with transistors and capacitors and what-not. We’re very primitive” (Church 2006).

political concern, whether they took the form of stem cells, resurrected flu viruses, or transgenic organisms.

After Hurricane Katrina struck New Orleans, George Bush announced in a speech that “Americans have never left our destiny to the whims of nature, and we will not start now.”¹² Endy circulated this quote to lab members over email, joking that Bush was advocating synthetic biology, a field that Endy justifies by claiming that evolution — the “whims of nature” — should not necessarily limit what biology *could be*.¹³ The first years of the new millennium were, in short, a moment in which U.S. political, sociocultural, ecological, biotechnical, and moral worlds were populated by biologies that had been made, and I was in the Endy lab to get a better handle on how the biological was being fabricated, and to what ends. But what does it mean for something to “be biological” — to borrow the felicitous phrasing of Hannah Landecker (2007) — at a moment when, increasingly, what we know about biology emerges in the process of fabricating novel biological objects?¹⁴ Further, what does it mean to “construct” biology, and what did it mean *to these particular people at this particular historical moment?* Constructing biology, I found, does a lot of work for synthetic biologists: biological artifacts are epistemic

¹² Of course, Bush’s refusal to be buffeted by the “whims of nature” was predicated on a falsehood — that the damage New Orleans sustained had been due to a “natural disaster,” rather than a technical, political, and social failure in which urban and race histories made low-income black communities particularly vulnerable to flood damage and its after-effects (Elliott and Pais 2006, Giroux 2006, Hartman and Squires 2006, Lavelle and Feagin 2006). Things deemed “natural” are nearly always things also made.

¹³ As Endy put it in an interview with the *Bulletin of Atomic Scientists*, “an engineer could describe evolution in the same way that the folks here [Boston] long ago thought about King George III: as mutation without representation — like, who ordered all this stuff? We can try to liberate ourselves from the tyranny of evolution — it’s the starting point in the synthetic evolution” (Siegel 2007: 31-2).

¹⁴ Landecker argues that biotechnology redefines what it means to be biological, such that biological substance is plastic, “suspendable, interruptible, storable, and freezable in parts” (2007: 228). Further, she contends that “being biological” is value-laden, requiring that we answer the question: “What is the social and cultural task of being biological entities — being simultaneously biological things and human persons — when “the biological” is fundamentally plastic?” (ibid: 235).

things that destabilize understandings of life (Rheinberger 1997), technical objects for building new biological systems, and social tools for building historically and institutionally specific social orders (namely, Open Source ethics of hacking, collaborating, sharing) into an emergent scientific community.

The MIT Synthetic Biology Working Group's self-described mission was to "[make] life better, one part at a time."¹⁵ *Making*, for synthetic biologists, means hewing closely to the principles of engineering, such as standardization, abstraction (black-boxing complexity across hierarchies), and decoupling (separating design from manufacture). For them, *life* is a natural resource and an untapped medium with which to design and fabricate engineered systems.¹⁶ It also may reference the professional and social lives of synthetic biologists, who hope that their current efforts are building a platform that in coming years will make it easier to do biology. *Better* means conforming more closely to the functionalist aesthetic of engineers. It is also a moral claim, along the lines of "the good life," which assumes openness and sharing to be inherently good. Synthetic biologists, note, are not interested in making life "best," because at the heart of their project is the notion that life is modifiable, and hence the work of engineering and reengineering is never finished. *Part* — the term most foundational to these practitioners — refers to a standardized, fully characterized, and modular biological component that performs a

¹⁵ This slogan calls to mind DuPont's advertisements for OncoMouse (TM), which Donna Haraway so nimbly critiques: "where better things for better living come to life" (1997: 84).

¹⁶ Adrian Mackenzie urges social scientists not to take the the notion of "design" in synthetic biology at face value, suggesting that one must pay attention to the question of *who designs* in synthetic biology. "design in synthetic biology is also a meta-technical practice in the... sense of meta, what comes after or beyond. Design is a meta-technique in that it organizes, groups, assembles and subsumes other techniques, practices, methods, protocols, knowledge, services and infrastructures into specific arrangements, while at the same time, appearing to stand outside them" (2010: 183).

human-defined function. The word's etymology recalls a distant but now relevant sense of the word: to share.

The agenda of synthetic biology, as stated by the Synthetic Biology Working Group, is twofold: 1) “the design and construction of new biological parts, devices, and systems,” and 2) “the re-design of existing, natural biological systems for useful purposes.”¹⁷ Major players in U.S. synthetic biology cite the adoption of engineering design principles as essential to this project. Synthetic biologists, inspired by digital logic, aim to design new biological parts, or “BioBricks,” that can be assembled into more complex biological devices and systems. In the process, they are also redesigning what it means for something to be biological. They hope that a library of standardized biological parts will be a foundational technology that could transform bioengineering from a mode of artisanal production to molecular Taylorism, in which parts or whole systems may be ordered from “biofabs” or “foundries,” DNA synthesis companies that fabricate made-to-order genetic sequences. The full Registry of Standardized Biological Parts now comprises around 5,100 parts, which are stored both digitally (as coding sequences) and materially (as plasmids suspended in the Registry’s freezers). These parts were built by synthetic biologists, and are almost exclusively used by synthetic biologists rather than “traditional” life scientists — 71 academic laboratories and 128 undergraduate student teams are currently enrolled Registry users.¹⁸ Indeed, as I will argue later, part of the reason BioBrick parts are

¹⁷ This charter is published on the homepage of the Synthetic Biology Working Group: <http://syntheticbiology.org/>

¹⁸ Of the undergraduate teams, 38 are from Asia, South Asia, and Australia, 10 are Canadian, 38 hail from Europe, 4 are Latin American, and 1 is African. The other 37 teams are from the United States.

exclusive to synthetic biologists is because their manufacture, use, and distribution is what constitutes the synthetic biology community.

Synthetic biologists bring three strategies borrowed from engineering to bear upon DNA, which they identify as standardization, abstraction, and decoupling (Endy 2005). These engineering principles are ubiquitous in synthetic biology, appearing in grant proposals, peer-reviewed publications, lab discussions, conference talks and poster presentations, and journalistic accounts of the field. It is unsurprising that these are the tactics synthetic biologists espouse, given that trained engineers first promoted their application to biology: Endy, for example, first studied structural engineering at Lehigh College,¹⁹ then received a PhD in biochemical engineering from Dartmouth College.²⁰ Tom Knight is a research scientist in MIT's Computer Science and Artificial Intelligence laboratory, and Gerald Sussman, whose work focuses on computing languages and artificial intelligence, is a Panasonic Professor of Electrical Engineering. Randy Rettberg, who maintains the Registry and orchestrates the annual iGEM competition, worked on ARPAnet and parallel processing before leaving Sun Microsystems to come to MIT. In this sense, synthetic biology is doubly a "trading zone," in that it both "[binds] together the disunified traditions of experimenting, theorizing, and instrument building" (Galison

¹⁹ Lehigh College is located in Bethlehem, Pennsylvania. Endy studied there in the final days of Bethlehem Steel, whose closure signaled for many the end of the United States's primacy in industrial manufacture. As an undergraduate, he earned money in the summer by working in roofing and construction, and compares the experience of working with genetic material to the pleasure of other, more menial labor: he recalls that "there's a visceral satisfaction to making a physical object. "But the first time I cut and spliced a piece of DNA, I felt the same joy of making something. I was like, 'Holy crap! It works!'" (Parks 2007).

²⁰ Explaining his disciplinary peripateticism, Endy said in a 2008 lecture, "There's one way to tell the story where I jump around from structural engineering to environmental engineering to chemical engineering, to genetics to cell biology, to biology to biological engineering, in this big loop. That's not it. If you do a frame of reference shift, the simpler way to say it is, I like to build stuff, and biology is the best technology we have for making stuff — trees, people, computing devices, food, chemicals, you name it. I somehow found my way to biology and, along with the ambition of getting better at engineering biology, there's this wonderful complementary puzzle of, how the hell does this stuff work?"

1997: 803)²¹ and is a field in which biotic artifacts, by incorporating engineering standards into living substance, coordinate disparate intellectual and practical histories.²²

Standardization, for synthetic biologists, means two things: first, arguing over and sometimes agreeing on standards for characterizing biological functions, akin to the social conventions that specify the length of a meter or the duration of a second or fraction thereof (Alder 2002, Canales 2010, Galison 2004, Smith 1977). Second, it means engineering standard biological parts that can be used interchangeably to collaboratively assemble multiple and diverse biological systems. A standard biological part, according to the 2003 BioBrick parts composition standard written by Tom Knight, must meet a series of requirements, including the absence of particular enzyme recognition sequences, the addition of DNA prefixes and suffixes,²³ and use of community-approved antibiotic resistance genes, plasmids, and bacterial strains.²⁴ These standards confer the advantage of making parts assembled by different synthetic biologists compatible as subcomponents of larger systems, so that practitioners can coordinate their work.

²¹ Peter Galison defines a trading zone as “an intermediate domain in which procedures could be coordinated locally even where broader meanings clashed” (ibid: 46).

²² That half of the MIT Synthetic Biology Working Group (the Knight Lab) was located in MIT’s building 20, the same building whose former incarnation had housed the Radiation Laboratory, from whose history Galison spun his theory of “trading zones,” evidences the historical strata beneath recent events.

²³ These prefixes and suffixes are restriction sites, DNA sequences recognized by restriction enzymes, which bind to DNA and cleave sequences at those sites.

²⁴ The first iteration of an assembly standard for biological engineering was drafted in 2003 by Tom Knight. The historical touchstone for standard biological parts is the US standard screw thread, which William Sellers proposed in 1864. Until Sellers defined a standard screw thread, screws in the US were disuniform. By proposing the design used in his own Philadelphia machine shop, with sides at an incline of 60 degrees, Sellers rendered screws interchangeable, so that they could be manufactured in bulk for the United States’s burgeoning industrial demands (for a history of Sellers’s standard screw thread, see Sinclair 1969). Assuming that biological parts will behave in a manner similar to mechanical components, synthetic biologists contend that standardizing biological parts will enable the sort of black-boxing now fundamental to mechanical engineering, in which parts operate interchangeably, systems may be manufactured without first fabricating dedicated elements, and design and fabrication are separate activities.

Further, the standard is meant to generate itself (it is “idempotent,” unchanged by combining it with other parts): two parts flanked by standard restriction sites, when assembled together, yield another part sandwiched between the same standard sequences. All 5,100 BioBrick parts conform to one of six standards (others were proposed by researchers at Harvard and Berkeley), but the vast majority of parts follow Knight’s assembly standard. The synthetic biology community works to agree upon the implementation of such standards, and does so in the hopes of furthering its own development. As synthetic biologists increasingly define themselves as bioengineers who work with BioBricks, the reliable assembly of BioBricks helps enroll new synthetic biologists. Building BioBricks is both a technical accomplishment and a form of political and social action.

The second engineering technique adopted by synthetic biologists, *decoupling* design from fabrication, is meant to allow biological engineers to design a genetic sequence encoding some function, and then outsource the physical synthesis of that sequence to a company. It is, in this sense, a way for practitioners to navigate a new research environment in which the physical manufacture of genetic material is outsourced from academic labs to commercial synthesis companies. Improvements over the last ten years in the speed and cost of genetic sequencing and synthesis have made possible large-scale genomic engineering. For example, the number of nucleotide bases that a single person can synthesize in an average workday increased from 200 to 10^5 between 1990 and 2000 (Carlson 2003). Between 1992 and 2003, the cost per base pair synthesized dropped nearly tenfold (*ibid*). Many synthetic biologists cite, in publications and

lectures, but also in informal conversations, advances in DNA synthesis as a foundational enabling technology of synthetic biology.

Abstraction, the third engineering technique synthetic biologists apply to living substance, is a way of managing biological complexity. The genome projects of the 1990s caused biologists to “begin to fathom [life’s] depths, marveling not at the simplicity of life’s secrets but at their complexity. One might say that structural genomics has given us the insight we needed to confront our own hubris” (Keller 2000: 8). This realization prompts engineers to try to tame, rather than marvel at, life’s complexity. Towards that end, synthetic biologists are developing an “abstraction hierarchy,” which, they hope, will function as a black box, allowing them to work on any level of biological complexity without taking into account the details of previous levels of complexity (Canton et al. 2008, Endy 2005). They explicitly compare their biological abstraction hierarchy to computer architecture, an analogy which, as I will later show, is meant not only technically, but also socially. The abstraction hierarchy parses biological entities into three categories: parts, devices and systems. A biological part, according to their definition, is DNA encoding a function. A device is a combination of parts that performs a human-defined function. A system is an assemblage of devices that performs some more

complex function. Materially, abstraction allows synthetic biologists to use parts in combination using defined part-part junctions.²⁵

Not everyone is persuaded by the promise of standardized and Open Source biological parts that synthetic biologists have peddled over the last ten years. Even those researchers who identify as synthetic biologists sometimes voice skepticism. The same realization of biological complexity that incites engineers to “refactor” or “streamline” living substance makes others question the foundational assumptions of synthetic biology. One Berkeley graduate student trained in biochemistry whom I met while he was working at the Endy lab blogged his misgivings, admitting to being “taken aback [while at MIT] at the engineering jargon and oversimplification” he heard synthetic biologists use to talk about biological “systems I knew were very complex and incompletely studied.” He felt that “biology is so complex, few things we do ever work as expected or intended” (Moser 2010). Synthetic biologists working in the University of California system, who were not reared in MIT’s hacking tradition, are much more circumspect about the reliability of BioBricks and the feasibility of treating biotic substance as an engineering substrate, as are new explants to synthetic biology from traditional biology backgrounds. One systems biologist argues that modularity is fundamentally incompatible with

²⁵ Life’s partibility here underwrites the abstraction of both market and ethical values from biotic things, marrying a faith in the predictable behavior of machines to an investment in the generative capacity of living substances. Social studies of contemporary life sciences submit that the “molecularization” of life entails a decontextualization of biological parts from their material substrates. For example, sociologist Nikolas Rose posits that “molecularization strips tissues, proteins, molecules and drugs of their specific affinities — to a disease, to an organ, to an individual — and enables them to be regarded, in many respects, as manipulable, and transferable elements or units, which can be delocalized (2007: 36). In synthetic biology, “molecularizing” life is premised on biology’s “natural” partibility: as Tom Knight said in a 2006 conference lecture, the “good news” for synthetic biologists is that “biology is modular and abstract:”

Evolution needs modular design as much as we do. How could we be so lucky?... Evolution can’t cope with complexity either. There’s no way evolution can independently mutate all of the pieces individually and in a complicated way to get to the point where it has sophisticated systems (Knight 2006).

biology: “In software engineering, modularity means ‘putting a boundary around some set of things’ to set it apart from the rest of the system.... But are biological modules the same? Can they be enclosed and made to communicate in restricted ways? Or are biological modules just too permeable?” (Gunawardena 2008, quoted in O’Malley 2009: 380). Many of the most prominent U.S. synthetic biologists, among them Drew Endy, Tom Knight, and Jay Keasling, who received PhDs in engineering fields and came to biology later in their careers, find such doubts risible. In a keynote address at a synthetic biology conference in Zurich, Tom Knight reassured his audience, “The good news is, biology is modular and abstract.” Contests over whether biology is abstractable, standardizable, and partible are not mere philosophizing, however. Because synthetic biologists build the social norms governing their lives and work into the things they make, the ontology of living things impacts how synthetic biologists’ practices get organized and implemented.

BIOLOGY AS SOURCE CODE

Alain Pottage has argued that “were the ambitions of synthetic biology to be realized,” it would “open up a kind of ‘life’ or ‘biology’ that is quite unlike ‘life’ as it is construed by existing biotechnologies” (2006: 144). I think claims such as this one buy into the promissory rhetoric of synthetic biologists, who claim to be very nearly about to remake “life as we know it.” More to the point, whether synthetic biologists’ ambitions are “realized” or not, their project, I maintain, would not be tenable if *life* were not already a troubled and troubling epistemological category; synthetic biologists treat life as a coherent and stable entity despite the fact that the very thing on the table is its material reconstruction.

The belief that biology can be understood through its construction is unmistakable in the way synthetic biologists describe their aims. Endy uses an analogy to physics to make this point: “Imagine what the science around the origin of the universe might be like if physicists could construct universes. It just so happens that in biology, the technology of synthesis [allows you to] instantly take your hypothesis and compile it into a physical instance and then test it” (Jha 2005). Rob Carlson, a synthetic biologist and garage biohacker who worked with Endy at Berkeley’s Molecular Sciences Institute in the 1990s, makes a similar comparison to engineering: “Understanding is defined by the ability to build something new that behaves as expected”; examples include both 777 jets and yeast cells (MIT lecture 11/07/08).²⁶ Many synthetic biologists quote Richard Feynman, who left this parting missive on his blackboard before his death: “What I cannot create, I do not understand” (1989).²⁷ This quote, they admit, is “a favorite among synthetic biologists — and for good reason,” because “synthetic biology is the pursuit of comprehending biological systems by trying to engineer them” (Carr and Church 2009: 1152). Endy paraphrased Feynman’s blackboard scribble when he says, “As a biological designer, until I can actually design something, I don’t understand it” (Sagmeister and Endy 2006). Two synthetic biologists offered the following definition of the field:

²⁶ Yet, Carlson cautioned, right now bioengineering is “more like the beginning of flight... than a 777” (ibid).

²⁷ Critiquing synthetic biologists’ use of “Feynman’s Last Blackboard” to justify their constructive approach, Maureen O’Malley points out that astrophysicists understand a lot about galaxies without making them and that, conversely, factory workers build electronic components without necessarily understanding how they work. Further, she argues that a closer reading of Feynman’s work suggests that “Feynman seemed to be suggesting that knowledge production is only sometimes driven or assisted by the construction of objects, and that design should be attuned to phenomena and practical necessity, not the elegance of the relationships between principles” (2009: 386).

Synthetic biologists seek to assemble components that are not natural (therefore synthetic) to generate chemical systems that support Darwinian evolution (therefore biological). By carrying out the assembly in a synthetic way, these scientists hope to understand non-synthetic biology, that is, 'natural' biology (Benner and Sismour 2005: 533).

Peter Dormer writes of making things, "For some people the method of exploring ideas through making is the best route to understanding those ideas or responding to a class of objects that already exist" (1997: 157). For synthetic biologists, "understanding" and "responding" to biology means treating it as a set of functions that may be instrumentalized towards remaking what biology *could be*. But what can manufactured biologies tell synthetic biologists about *life* writ large? And how do such bespoke biologies speak to "natural" biologies? In part, these artifacts hybridize and complicate distinctions between "natural" and "artificial," biotic and computational (and, as I later will claim, join biologies to socialities), as well as scramble taxonomies transgenically. More than helping synthetic biologists "comprehend" biological systems through their assembly, these objects seem to disassemble biology's referent.

For example, one notable synthetic biology project is the work of the J. Craig Venter Institute to synthesize and boot up a "minimal" organism (Gibson et al. 2008), a single-celled entity that maintains the minimum amount of genetic information necessary to sustain life. Venter and his employees imagine that manufacturing such a biological entity will help them to better understand the contours of "life:"

The J. Craig Venter Institute uses mycoplasmas as platforms to learn the first principles in the design of cellular life.... For any given unknown protein or molecular machine, the knowledge of its transcriptional regulation and protein-protein associations can be the

catalyst for... advancing one step closer to the long-sought understanding of cellular life at its simplest and most fundamental level” (Glass et al. 2009: 2).

In synthesizing and assembling the *M. genitalium* genome, researchers at the J. Craig Venter Institute developed a technique whereby the genome was split into short DNA “cassettes” that were cloned into *E. coli*, then assembled in *S. cerevisiae* (the authors patented this method in November 2009).²⁸ Synthesizing this genome, synthetic biologists hope, will help them determine “the essential genetic functions for life” (Gibson et al. 2008: 1215). Venter hailed the resulting “minimal” genome, cultivated in both eukaryotic and prokaryotic cellular substrates, as the “first new artificial life form on Earth” (Pilkington 2007), thereby “making a metonymic substitution of ‘code’ for ‘organism’” such that “the organism is ‘contained’ or engulfed” by genetic material (Doyle 1997: 28).²⁹ This was the first step in a larger project to manufacture a new, independently living, organism bearing a minimal genome. In 2010, the Venter Institute announced that it had synthesized and assembled a synthetic version of the *M. mycoides* genome, inserting it into *M. capricolum* cells.³⁰ While this was not *de novo* life — the nucleotides no

²⁸ They also inserted “watermarks” to identify the genome as synthetic, like painters signing a canvas or boys scrawling their initials in a tree trunk: CRAIGVENTER, VENTERINSTITUTE, etc.

²⁹ In a comment published in the same issue of *Science* in which the Venter Institute announced its synthetic genome, Drew Endy commented that the authors had “bypass[ed] nature’s constraint of direct descent by combining information and raw chemicals to construct the entire set of genetic material, or genome, encoding a bacterium” (1196). He then complained about the limits of current methods in bioengineering: “the required slavish mastery of ad hoc methods and tedious tools for DNA manipulation discourages most students and researchers in fields such as physics, electrical engineering, and computer science from exploring biomedical and biotechnology research,” suggesting that better techniques might improve current methods for identifying genetically encoded functions, which he compares to “blindly smashing many cars with a hammer and then determining which broken parts matter by attempting to drive each machine” (ibid). What synthetic biology presages, he argues, is “a powerful new ‘hammer’ for constructing how life works” (1197).

³⁰ Venter’s announcement prompted President Obama to charge the Presidential Commission for the Study of Bioethical Issues to draft a report on synthetic biology. In a May 20, 2010 letter to Amy Gutmann, the Commission president, Obama wrote: “for the first time, all of the natural genetic material in a bacterial cell has been replaced with a synthetic set of genes. This development raises the prospect of important benefits, such as the ability to accelerate vaccine development. At the same time, it raises genuine concerns, and so we must consider carefully the implications of this research” (unpublished letter).

doubt were harvested from sugar cane or salmon milt, portions of the genome were inserted into yeast cells for assembly, and the genome itself was hosted and replicated by a recipient bacterium — Venter announced that his team had made “the first self-replicating species we’ve had on the planet whose parent is a computer” (Wade 2010).³¹

Venter is not the only synthetic biologist to work on stripping “life” down to its most “primitive” form — others have performed multiple reductions to *E. coli* genomes in order to construct “*tabula rasa*” bacterial strains (Posfai et al. 2006); researchers at The Rockefeller University engineered a “protocell,” establishing that transcription and translation may be performed external to the cell in unilamellar vesicles. They defined the basic components of “life” as being “an enclosed space displaying exchange and use of external energy/nutrients through a semipermeable membrane” (Noireaux and Libchaber 2004), later referring to their “artificial cells” as “small, enclosed laboratories” (*ibid*). Such streamlined biotic systems also function as biological origin stories — at a synthetic biology conference in Zurich, researchers presented their work to remove all genes “unnecessary for life,” leaving them with a “minimal although limping [*Mycoplasma genitalium*] cell” that they claimed was “a model for early living cells” (Murtas 2007). Another researcher presented theoretical work on identifying a “paleome” — finding those persistent and highly conserved genes whose “organization reflect[s] the scenario of the origin of life” (Danchin 2007).

³¹ Synthetic biologists named the chimeric bacterium “Synthia,” a name that conjures the gender politics of technical birthings. It also reminds me of another meaning of “synthetic” — something fake or false — a gloss that was made apparent when biologist David Baltimore commented to *The New York Times* that Venter had “not created life, only mimicked it” (*ibid*). As Helmreich has argued in regards to computational versions of artificial life, life, like gender, “does not consist of a set of natural properties,” but is instead “a set of behaviors amenable to imitation” (1998: 247).

One project pursued by the Synthetic Biology Working Group during my fieldwork clearly demonstrated the confluence of knowing and making at the heart of synthetic biology. The enterprise, helmed by Endy and graduate students Sriram Kosuri and Leon Chan, aimed to streamline the bacteriophage T7, a virus that infects *E. coli*, by separating the virus's overlapping genetic elements and removing DNA that had no known function. They named the first iteration of this experiment, which tested the viability of a virus synthesized *de novo* for ease of modeling and manipulation, T7.1, following the naming conventions of software releases. As a graduate student and postdoc, Drew Endy unsuccessfully had attempted to develop a computer model that could predict the behavior of T7, a model organism widely used in biology labs since its isolation in 1945. One of his first computer models incorrectly predicted that a mutant bacteriophage would grow faster than wild-type T7. Faced with the realization that bacteriophage was poorly understood, the synthetic biologists decided that the best way to learn more about it was to synthesize one. As Kosuri explained their reasoning,

We could continue to make our models ever more detailed in hope of better characterization. Alternatively, we decided to design and construct a surrogate phage that is easier to understand and model (unpublished manuscript).

They annotated the genome, defining the boundaries of open reading frames, ribosome binding sites, and regulatory elements. They then split all of these elements into seventy-three discrete parts, and distributed those parts into six sections, which they built and tested separately. After synthesizing each section, they transfected it into T7 to construct chimeric phages, on which they tested viability and infectiousness (Chan et al. 2005).

Making things in synthetic biology may be the royal road to understanding life, but what did synthetic biologists hope to learn about bacteriophage by fabricating a chimeric streamlined virus from scratch? Certainly the resulting biotic artifact bore little resemblance to T7, the biology workhorse. I asked Kosuri over coffee in September 2005: What is T7.1 a model *of*? Kosuri laughed, telling me this was a question he often fielded: “We don’t care whether it’s a natural isolate,” he said, because “in the end... it’s still physical proteins interacting with each other.” Further, he reminded me, it was not like T7 was “natural” when they started working with it: it had been tailored by and to laboratory biology for over sixty years.³² He admitted that he and Endy often joked about dumping a bunch of T7.1 in front of the *Sorcerer II*, the ship in which Craig Venter sampled seawater to sequence the “ocean’s genome.” As soon as Venter dredged up a bucketful of Chan and Kosuri’s patched-up virus, he said, it would again be a “natural” isolate. T7.1’s epistemological warrant does away with distinctions between “natural” and “artificial” forms of life, subsuming them both under the shorthand *life*. Synthetic biologists seek to explore life as a conceptual category by constructing limit forms of life in the laboratory, such that conjectures about what life could be destabilize notions about “life.”³³

Projects such as Venter’s synthetic bacterium, T7.1, and others toy with what might count as the “limits of life” (Helmreich 2008a, forthcoming), from reverse engineering what

³² Synthetic biologists are attuned to how their enterprise reframes notions of the natural and artificial with respect to biology, as was demonstrated to me while eating dinner with Drew Endy and Paul Rabinow in March 2006. Endy, after a few glasses of wine, posed a question to the table — he told us that people were always asking him whether he could imagine an environment that would naturally give rise to T7.1. Jokingly, I answered, “Yeah, it’s called a synthetic biology lab.” Drew grinned — “Exactly!” This was the answer he gave when asked the same question. Rabinow, amused that I could correctly predict Endy’s response to this question, quipped, “See? There *is* such a thing as a social science!”

³³ This work might be situated within a longer history of biological thinking about life forms, which proceeds from induction, to deduction, to abduction, and finally to construction. See Helmreich and Roosth 2010.

researchers imagine to be the “first” life-form to stripping down microbes to determine a “minimal” genome. Helmreich argues that “limit biologies” such as these “indicate instabilities in the ‘nature’ supposed to ground ‘life.’ And they all do so through a wiggling of what is meant by the ‘form’ that life takes, a loosening that suggests epistemic shifts in the biological sciences more generally” (forthcoming: 22). Engineering new biotic things, it seems, destabilizes life, turning it into an “epistemic thing,” obliging biologists to ask after its origins and its material and informatic limits. In constructing new biotic things, “life” also ends up under construction. Epistemic things, such as objects of molecular biology, Hans-Jörg Rheinberger argues, are dynamic, hybrid, experimental units that “embody what one does not yet know” (1997: 28), both unsettling scientific facts and pointing towards new epistemic knowledge. Following this argument, I claim that the products of synthetic biology are physical instantiations of what biologists know (and assume) life to be, as well as persuasive objects that materialize analogies that compare living things to engineered things: genetic material as source code. Another way of putting this is: these objects are both materialized hypotheses about life and experimental data. In the history that follows, I delve into the disciplinary and institutional origins of the analogy of genetic material to Open Source-able source code, and show how it colors synthetic biologists’ technical, practical, social, and moral commitments.

HACKERLY SOURCES OF SYNTHETIC BIOLOGY

The story about how the moral and technical values of Open Source were ported into bioengineering is, by no accident, set at MIT. The story that follows is about how a famous computer hacker went back to school to become a synthetic biologist. Synthetic biology

emerged in Cambridge in the late 1990s and early 2000s, very much the fruit of MIT's hothouse of hackerdom, as well as the many biotech, Internet, and pharmaceutical boutique companies that grow thick on the ground in nearby Kendall Square, which had been a derelict cluster of factories until NASA and Raytheon moved in in mid-century. In order to explain how synthetic biology got its start, I must first introduce Tom Knight. When I met Knight, a scientist, hacker, and public figure affiliated with Science Commons and other Open Source groups, he had already been at MIT for over forty years. With a graying Lincoln beard and eyes that suggest he is laughing at a joke that you are not in on, he describes himself as "your basic geek." Knight came to MIT in the early 1960s at the age of fourteen and loved it so much he never left. He started doing computer science in Marvin Minsky's lab at a time when immense computers worked using punch cards and batch processing, and he regards his move to synthetic biology as both a disciplinary and biographical yield.³⁴

In 1989, Knight was a research scientist in MIT's Computer Science and Artificial Intelligence Laboratory, and was best known for having been among the first generation of

³⁴ Though I often saw him around the MIT campus, I had a hard time, a year into my fieldwork, getting in contact with Knight to schedule an interview. He never responded to my emails, and always seemed to disappear from crowded rooms when I tried to corner him to talk. After several of my emails went unanswered, I asked his grad students to help me get in contact with him. They recommended that I encode my email in nucleotides, saying that Knight would feel compelled to decode it, which would mean, at the very least, that he would read my email. I sent him two pages of As, Gs, Cs, and Ts. The first few sentences read:
GGTAAACGGTTCGCTTGTGTGTTGGTTTGCAGGGGTGTGTTGCGGGGTGCATGACACTGCTTGTATGCGTT
TGGGGGTTTGTGCGTGCTTTGAGGGGTGCTTTGAGGGGTTGATGAATTGGTGCGTGCTTGGTGGGGTTG
CTGAATGAATTGATTTGTGCGGGGGTGTGATGGGGTGGTTGACACGGGGTGGTTGACACTTTGTGCG
TTGCTGAATTGGTGAATGAGTGAATGTATGCTTTGATTTGGGGGTGAATGTCGGGGTTGATGGATGCTTG
TTGACACTGGATGTTGGGGTGTGCTTGACACGGGGTGGTTGCTTTTGTGAGGGGTTGATTTGTTGAGGG
GTTGGTTGCTGAATGTATTGCTGGTTGATGGGGTGGTTGACACTGTGGGGGTGGTTGATGGGGTGTGTG
AATGCTTGACACTGTAGGGGTTGGTTGCTGTTTGTGTGCTTTGATTGATGTTTTGCTTTGTGGTTTTGTG
TTGAATGACACGGGGTTGCTGTTTTGATGTTTGGTTTGTGCTGGATGCGGGGGTGTGACACGGGGTTGA
TTCTTGACACTTTGTGCGTGTTTTTGTGCTTGGAGGGGTGGCTGCTTGAATGAGTGAATGTATTCTGGGG
ACAG (dear dr knight this is sophia rooth im an anthropologist of science in mits sts program and am doing
predissertation research in synthetic biology as part of my research ive been doing fieldwork in drews lab since last
august). The ploy must have worked — the next time I saw Knight, he agreed to an interview.

computer hackers, when he worked on ARPANET and helped develop the Lisp machine, which made hacking possible by enabling a single person to work on a single workstation. Things radically changed for Knight when he read an unpublished proposal by biophysicist Harold Morowitz to sequence and analyze the genome of the simplest known organism (he conferred this honor upon organisms of the genus *Mycoplasma*, a species of which was the object of Craig Venter's early attempts to synthesize an organism of minimal genome) (Morowitz 1988, Morowitz and Tourtellotte 1962). Morowitz has been affiliated for several decades with agencies like NASA and DARPA, with whom he investigated questions related to other limits of life: the search for extraterrestrial life and the origins of life. In an article published in *Scientific American* in 1962, Morowitz wrote of *Mycoplasma*, "The existence of such a small cell raises intimate questions about the relationship of molecular physics to biology" (120), suggesting that if biology could simply be made *small* enough, its secrets would be amenable to investigation by physics rather than biology.³⁵

Knight was riveted by the simplicity of the organisms Morowitz was studying. Until he read Morowitz's article, Knight had felt that biology was "so hopelessly complicated that I had no hope of understanding it." Discouraged by the complexity of biology, he felt that it looked too "grim" for him to make any serious headway in the discipline. Morowitz's work made him reassess the feasibility of meaningfully intervening in biology. As Knight told me, "600 [genes] is a small enough number that at least as an electrical engineer I could fool myself into thinking

³⁵ For an account of how physics and information theory influenced molecular biology in the mid-twentieth century, see Kay 2000.

that I might have some hope of understanding what was going on.”³⁶ As I have already claimed, such limit forms of life — minimal organisms, streamlined genomes, and putative “primitive” or “early” living things — underwrite much of synthetic biology, as they stand for both easily *understandable* living things, shorn of the complex ramblings bequeathed by evolution, and as easily *fabricated* living things, with genomes small enough to be compiled by present-day synthesis technologies. Such “simple” biological things persuade practitioners that biology is both makable and understandable, and further, that the knowing may follow from making.

In August 1996, Knight submitted to DARPA a proposal to study synthetic biology. At the time, he and the other scientists (hailing from MIT, Harvard, Yale, Chicago, Stanford, the Whitehead Institute, as well as the Woods Hole Oceanographic Institute [WHOI], DARPA, and the NSF) who were interested in developing technologies that would turn biological engineering into a form of manufacturing akin to electrical engineering — with prefabricated components, standards collated and printed in parts catalogs, and large-scale industrial manufacture — were faced with a dilemma. They wanted to call themselves bioengineers, because their aim was to turn biology into an engineered thing, but bioengineering was already associated with an established field that had grown up around recombinant DNA technology and PCR.³⁷ To

³⁶ He summarized this shift in thinking, “all of a sudden what at least as an undergraduate and high school student I had crossed off as, ‘Oh my God, no one will ever understand this, certainly not in my lifetime’ to a, ‘Gee, you know, here’s an organism that’s not that many pieces. We have a good shot at knowing what all those pieces are.’”

³⁷ Recombinant DNA (rDNA) technology, developed in the 1970s, allows nucleic acids from two or more different organisms or species to be “spliced together” in a single genome; polymerase chain reaction (PCR) is a method of making many copies of a physical DNA sequence (see fn 7). The difference between rDNA and PCR and synthetic biology is this: rDNA and PCR work with segments of nucleic acids harvested from some biological source, while synthetic biology relies on nucleic acid synthesis technology, which allows researchers to specify entirely new sequences that are synthesized from single nucleotides (DNA and RNA bases). To abuse the hoary textual metaphor, it is the difference between working with whole sentences or paragraphs of text versus single letters of the alphabet. While this difference may seem niggling outside the field, the ability to synthesize genetic sequences “*de novo*” makes all the difference for synthetic biologists, who consider it the difference between “scavenging” for “found” genetic sequences and designing new sequences to meet specific requirements.

distinguish themselves from this earlier, and they felt inaccurately labelled, version of bioengineering, they scrambled to find a new handle. Knight and his crew, who had already been at work on what they then called “amorphous computing,” eventually settled on “cellular computing.”³⁸ Knight secured from DARPA a short-term (three to four year) contract, using it to set up a biology lab in Cambridge’s Technology Square. He credits the fact that none of the people working in his lab were professional biologists, and that the lab was not even equipped to be a biology lab (no fume hoods, autoclaves, ice machines, or hazardous waste disposal, for example) for his early successes in developing BioBrick parts:

I guess the way you learn is by going out and doing things and realizing that they don’t work. That’s certainly the way I learn how to do things. I don’t regret the fact that we spent the time making those mistakes.... If you don’t make the mistakes yourself, then the reason why you do things a specific way tends to remain a mystery.

Knight built the first six BioBrick parts, which he says were “inspired by his love of Legos” (Restuccia 2009). He also first developed the idea of building a toolkit of standardized biological parts.³⁹ BioBricks, the foundational tool of synthetic biology, *were effectively developed to make biological engineering accessible to non-biologists*, and in particular to

³⁸ It would be another decade before the field was officially named “synthetic biology.” In 2000, scientists at Berkeley’s Molecular Sciences Institute, including Drew Endy, sent a letter to DARPA seeking funding for what they called “Open Source Biology.” A 1999 *Nature* article cited both “modular biology” and “synthetic biology” to talk about borrowing principles from computer science to study cellular function (Hartwell 1999). Rob Carlson, Roger Brent, and Drew Endy wrote a project proposal in 2001 to build “biological input/output capability,” calling their project “synthetic biology.” As far as I can tell, the field was not called synthetic biology at least until Knight secured DARPA funding for his research: the DARPA/ONR contract was titled “Computing with Synthetic Biology.” Synthetic biologists themselves did not settle on “synthetic biology” to designate their movement until it appeared on the cover of *Nature* in November 2005.

³⁹ Many synthetic biologists cite Legos, as well as other childhood toys such as Lincoln Logs, as inspiring their first love for building things. BioBrick parts are explicitly compared to Legos, and numerous illustrations of synthetic biology in the popular press include some image of DNA-as-Legos. Such imagery furthers the field’s self-presentation as motivated by carefree, almost childish, enthusiasm.

engineers who are used to working with standardized and characterized parts. In effect, they are “black boxes,” physical objects meant practically to serve as crystallizations of experimental biological knowledge so that their assembly does not require unpacking or utilizing prior information (Latour 1987).⁴⁰ But they not only make biology easier to do by computer engineers, they also install a particular strain of software culture in biotic substance.

Espousing a hacking ethic, Drew Endy aligns himself with the Free Software/Open Source (FS/OS) movement, a software culture whose members argue about the meaning of “Open Source,” share source code, debate the nuances of “openness,” utilize copyright licenses, and work collaboratively (Kelty 2008: 14-15).⁴¹ When Endy was at MIT, he and his students were outspokenly liberal members of these communities. Endy decorated the cover of his laptop with a Science Commons sticker, which faced the audience when he gave talks.⁴² In working to apply computer science and engineering techniques to designing biological systems, Endy collaborated with Hal Abelson, an MIT professor of computer science who helped found Creative Commons. Free Software and Open Source commitments were palpable in every aspect of the Synthetic Biology Working Group, and felt nearly religious in its totalizing influence on work and play among the lab members. In conversations, Endy’s students compared his role in the Synthetic Biology community to that of Richard Stallman, founder of

⁴⁰ Craft critics refer instead to “distributed knowledge:” “a category of tool and artefact that allows us to make things without ourselves possessing the know-how to make them” (Dormer 1997: 139).

⁴¹ Though the term “hacker” “tends to connote someone subversive and/or criminal,” synthetic biologists I talked to did not use the term in this sense. For them, hacking was about finding elegant solutions to difficult problems, was similar to but not synonymous with Free Software and Open Source, and also gestured towards MIT hacking traditions reaching back to the 1950s. For an account of how such histories become “usable pasts” for present-day hackers, see Kelty 2008.

⁴² Science Commons is a project working to apply the flexible licensing pioneered by the non-profit Creative Commons Corporation to science.

the Free Software Foundation and the GNU project. The comparison was a telling one — Stallman also got his start at MIT, working in the Artificial Intelligence lab with Tom Knight long before the latter founded the BioBricks Foundation with Endy. Whether consciously or unconsciously, Endy had adopted much of Stallman’s approach — they both saw technical progress as inseparable from the project of reengineering the reward structures in science, and Endy is a strong advocate of the Free Software Foundation founded by Stallman and supported by Tom Knight and MIT professors Gerald Sussman (a founding member of GNU and Creative Commons), and Hal Abelson.⁴³

Training to become a synthetic biologist at MIT, as I learned in graduate courses in bioengineering and in Endy lab meetings, required that students speak fluently in engineering and computational idioms. In a journal reading group I attended, we spoke about evolution as a “a uniquely powerful design feature.” Instead of cells, we would talk about “cellular networks” or “chassis,” biochemistry became “biochemical computation,” transcription factors and binding domains functioned within “logical circuits,” “negative and positive feedback loops,” “oscillators,” and “toggle switches.” Modifying RNA and DNA in viruses and single-celled organisms was, following software design conventions, termed “refactoring.” Certainly, in using these expressions, synthetic biologists were making an analogy of the biotic to the electronic, and by extension of biological engineering to electrical engineering. But while it would be easy to claim that synthetic biology is a field built upon an analogy, something more substantive is afoot

⁴³ Stallman, no longer an active programmer, now devotes himself full-time to advocating free software. The comparison of Endy to Stallman also points to an institutional tension: Stallman could not square his politics with those espoused by MIT, and in 1983 he left the Institute — without a PhD — to found GNU after his lab imploded due to intellectual property arguments (though he retains a position as a visiting scientist in MIT’s Computer Science and Artificial Intelligence Laboratory). Endy would leave MIT for Stanford in 2008, for both personal and political reasons.

with such language. Conversations in which bacterial colonies function like oscillators are not simply poetic. In part, these scientific pidgins are made possible by the disciplinary and biographical convergences particular to MIT.⁴⁴

Lab members peppered their speech with hacker lingo: a clever solution to a difficult problem was a “hack,” and to intuitively and deeply understand something was to “grok” it.⁴⁵ Instead of “publishing” a paper, they talked about hurdling peer review as either “celebrating” their work or “sharing ideas.”⁴⁶ Synthetic biologists’ allegiance to free software and Open Source movements is consistent with their constructive approach to learning about things biotic: legal scholar Wendy Seltzer claims that craftwork and copyright maintain an uneasy relationship with one another, in part because “craft may build upon found objects or others’ designs; artisans have always learned their trade by copying their predecessors, picking up a pen, brush, or chisel

⁴⁴ Learning to speak synthetic biology is a learning curve for most researchers, as biologists learn computer science jargon and engineers learn to speak biology. One example of this struggling towards linguistic proficiency comes from the synthetic biology journal club in which I participated. When one student presented a paper, she made several mistakes in her pronunciation of various enzymes and proteins, for example, calling the “LuxI” protein family “lux-one,” and the autoinducer AI, “A-one.” When another student pointed out her error, she blushed in embarrassment only to have Endy school the assembled undergraduate and graduate students on good manners in trading zones: “As engineers working in biology, you’ll interact with people from different cultures, and if you’re not paying attention, you won’t understand why a biologist thinks you’re an idiot. But it’s just because you haven’t studied phage lambda for thirty years. It’s just a mismatch.”

⁴⁵ *Grok* was coined by science fiction author Robert Heinlein in his 1961 novel *Stranger in a Strange Land*. While never clearly defined, *grok* was a Martian word meaning, “to understand completely.” The word was later picked up by hippies and computer programmers, and remains a mark of geek-cool. *The Jargon File* offers the following definition:

[from the novel “Stranger in a Strange Land,” by Robert A. Heinlein, where it is a Martian word meaning literally “to drink” and metaphorically “to be one with”] The emphatic form is “grok in fullness.” 1. To understand, usually in a global sense. Connotes intimate and exhaustive knowledge. Contrast zen, which is similar supernal understanding experienced as a single brief flash. See also glark. 2. Used of programs, may connote merely sufficient understanding. “Almost all C compilers grok the void type these days.” (<http://www.catb.org/jargon/html/G/grok.html>).

⁴⁶ In a field that is overwhelmingly committed to Open Source licensing, euphemizing publishing as “celebrating” implicitly disavows authorship as a way for synthetic biologists to establish intellectual property rights. It also points to one of synthetic biology’s ambiguities: while authorship in experimental science rewards original expression, engineering living systems fits more squarely with patenting and licensing law than authorship, as the product is an artifact rather than an expression (Biagioli 2003). On the other hand, the term “celebrate” can apply to both experimental and engineering work — one can “celebrate” both discoveries and artifacts.

first to imitate, then to reinvent” (2008). Many contemporary craft movements identify as Open Source, ostensibly claiming that Open Source regimes encourage the “creativity” by which crafters may build upon and be inspired by the artifacts around them. So too with hackers, who claim that collaboration yields “better” software (Kelty 2008). Given synthetic biology’s practical ties to software hacking and its constructive ethos, it makes good sense that synthetic biologists are concerned with intellectual property and norms of practice towards making biology “that does not suck” (Kelty 2001: 3 of 17). In an early meeting with Drew Endy, I asked him why he was passionate about open sourcing synthetic biology. His response was, “I don’t want wheat fields in 2010 to operate like Windows 95.” What such thinking means is that before synthetic biologists can make good biological artifacts (or, to borrow their slogan, before they can “make life better”) — that is, well-made objects of virtuoso skill and technique that behave as expected — they must first remake *themselves* as a community. It is in light of this social engineering that the circulation of standardized biological parts and the overwhelming pedagogical and media campaign waged by synthetic biologists — events like the International Genetically Engineered Machines Competition (iGEM) — factors in.

SOURCE SPECIES AND OPEN SOURCE

Synthetic biologists are assembling the biological and the social at the same time, and their artifacts are both produced by and constitutive of social assemblages committed to Open Source ethoi. In his ethnography of free and open software culture, Christopher Kelty forwards the concept of “recursive publics,” defined as “publics concerned with the ability to build, control, modify, and maintain the infrastructure that allows them to come into being in the first place and

which, in turn, constitutes their everyday practical commitments and the identities of the participants as creative and autonomous individuals” (2008: 7). So too with synthetic biology. Synthetic biologists argue about and sometimes agree on standards for biological parts so that those parts may then circulate (they hope) smoothly and transparently among a growing number of researchers. That is, the community and the parts are mutually composed. While synthetic biologists consider BioBricks simply to be an enabling technology, a condition to be satisfied before they can get on with the *real* work of synthetic biology, I argue for BioBricks also being socially constitutive: the cluster of activities enabled by such parts — sharing, synthesizing, assembling, modifying— are the activities by which synthetic biologists, as the manufacturers of these biotic artifacts, not only assemble biological systems, but also assemble themselves.

Anthropologists of craft have already noted that making things and making selves are entangled activities. As Michael Herzfeld has claimed of how apprentices in a Cretan town learn how to be full-fledged artisans, “the relationships among objects reproduce the relationships among selves.” (2003: 52). Dorinne Kondo argues similarly with regard to Japanese artisans who, in learning to make “traditional” Japanese crafts, also fashion multiple, contradictory, and performative “selves” (1990, see also Lave and Wenger 1991, Terrio 2000, Yanagisako 2002). However, neither Herzfeld nor Kondo claims that there is anything specific *in* or *about* the objects being manufactured that shapes social practices and imaginaries. Within science studies, scholars have paid attention to how biological things and the communities who make and steward them are also mutually constituted. Most relevant here is Robert Kohler’s history of *Drosophila* geneticists, in which he extends E.P. Thompson’s notion of “moral economy” to

argue that model organisms bred for laboratory research possess a “politics.” Further, he suggests that the politics of fruit flies undergirded the development of an informal network of geneticists who freely exchanged them. This dense exchange network effectively standardized laboratory *Drosophila*, and further functioned as a material medium with which to exchange tacit knowledge by circulating the products of researchers’ craftwork (1994).⁴⁷ Transfecting ethnographer’s claims that making things produces selves into historians’ accounts of how tamed and tended organisms can build exchange economies, I claim that synthetic biologists build BioBricks to install Open Source socialities in these parts and to draw together practitioners under the shared signs of standardization and openness.

The biology synthetic biologists construct is one in which biological and social understandings of relatedness, value, and generativity get scrambled, as do categories like nature and artifice. The parts now catalogued in the Registry must meet community-approved standards, including, as detailed earlier, the insertion of genetic prefixes and suffixes and the use of approved plasmids and anti-bacterial resistance genes. These standards are meant to make the parts interchangeable between synthetic biologists working on different projects; they are freely licensed in hopes that the strains will be shared among synthetic biologists. That is, standards are put in place, argued over, and sometimes agreed upon in order to breed openness. As the slogan of the BioBricks Foundation, plastered on t-shirts, bumper stickers, and the signature lines of synthetic biologists’ emails, repeatedly enjoined me: “Share your parts!” This version of “construction” is an MIT-specific, hackerly and Open Source approach to biological

⁴⁷ For histories of model organisms, see also Creager 2002, Rader 2004. For my review of the literature on model organisms in laboratory research, see Chapter 1.

construction, one that trades on the equation of DNA to source code and then posits that such code must be editable and shareable. The parts are designed to promote and maintain a “moral economy” among synthetic biologists, one in which they edit, tweak, improve, characterize, and — most importantly — generously share their biotic research tools. The standardized biological parts they construct thus embed the values, norms, and aspirations of their community of practice. Socially, much of this work gets done during the annual International Genetically Engineered Machine competition hosted by MIT.

iGEM began as a course taught during MIT’s 2004 winter break Independent Activities Period, in which a team of undergraduates calling themselves the “Polkadorks” engineered an “*E. colibrator*,” a bacterial culture in which, as Endy explained in an MIT lecture, “all the cells flip a coin and one sends out a signal, the other cells swim toward it, and the system resets.” That summer, the course was expanded into a competition in which 5 undergraduate teams built genetically engineered biological systems. iGEM has since grown every year, from 13 teams in 2005, to 32 in 2006, to 54 in 2007, and 84 in 2008. The 2009 competition drew 1,100 competitors in 100 teams (Smolke 2009).⁴⁸ The competition is funded primarily by MIT, the BioBricks Foundation, and the NSF-sponsored Synthetic Biology Engineering Research Council (SynBERC). The Registry mails a kit of BioBricks to student teams participating in the competition, with which they engineer a new biological system. As a condition of entry to the competition, each team is obligated to freely share any BioBrick parts they build by giving them

⁴⁸ Student projects range from the practical to the playful: one team manufactured bacteria that can detect and visibly respond to arsenic contamination in drinking water, another manufactured *E. coli* that smell like bananas, another built a bacterial calculator, using reengineered *Salmonella* to model the mathematical sorting problem known as the Burnt Pancake Problem.

(both the part's genetic code and a physical sample) at the competition's end to the Registry of Standard Biological Parts, maintained by the BioBricks Foundation.

The annual iGEM competition, or “Jamboree,” as it is called, has the air of a big-tent revival. Attending the awards ceremony of the 2008 jamboree, I sat near the back of MIT's Kresge auditorium, to better observe the sea of 750 college students in brightly colored team t-shirts. While the competition judges adjourned to decide the winners, someone cranked up the music on the auditorium's speakers, and soon hundreds of students were out of their seats and on stage, dancing to radio-friendly hip hop like OutKast and Beyoncé. These teenagers, hailing from schools from Hong Kong to Ljubljana, were really, really excited about synthetic biology, cheering wildly when research scientists came on stage to expound on the promises of synthetic biology or to announce the competition's winners.⁴⁹ Though iGEM has gotten a considerable amount of good press and funding for encouraging undergraduates to try their hands at bioengineering and share their results, the competition is not without its detractors and critics. Endy commented in May 2008 that the NSF had expressed concern in an in-site visit report that iGEM was engaged in “making biohackers,” which he dismissed by saying that iGEM was making “white hat” (i.e. good) hackers, not “black hats.” At its core, though, iGEM is about making synthetic biologists, which it accomplishes by making students build, borrow, edit, and share BioBrick parts. It tries to convert undergrads interested in biology, bioengineering, or computer science to synthetic biology by teaching them how to work with standardized

⁴⁹ There is, however, a darker side to iGEM: as Christina Smolke, a synthetic biologist at CalTech (and Endy's wife) reported in a commentary column in *Nature Biotechnology*: “Many students are so disappointed when their team does not make it to the list of finalists that they can be seen crying after the finalist announcements. There are also stories that the amount of time some teams dedicate to their projects is so intense it can be detrimental to other parts of their lives, often leading to the break up of personal relationships” (2009).

biological parts, and to reward them for adhering to the norms of the synthetic biology community, of which freely exchanging materials and information is foremost. Synthetic biologists even draw a parallel between assembling and distributing standardized biological parts and assembling and distributing new synthetic biologists. As Randy Rettberg said in a conference lecture reporting on the 2006 iGEM competition, “We *manufactured* 450 synthetic biologists and we shipped them out to the world” (Rettberg 2007, emphasis added).

Synthetic biologists, like Kohler’s drosophilists, also aim to develop a non-monetary exchange network for biological parts, but they are attempting to forward-engineer the system by establishing standards for biological parts in advance of their circulation. Rather than the standards being the *outcome* of local labor practices that materially accumulate in biological substance, thence to become standardized by dint of their pervasiveness, researchers put BioBrick assembly standards in place as technical fixes that would establish and enable future constellations of synthetic biologists to seamlessly exchange parts with which to fabricate larger systems. This also means that synthetic biologists are trying to forward-engineer *themselves*, as a community built upon the ethos of openness propagated by groups like the BioBricks Foundation and the Registry of Standard Biological Parts and events like iGEM.⁵⁰

⁵⁰ Graduate students in synthetic biology mused aloud about how best to “attract like-minded people” to the field and how to “disseminate the values” of synthetic biology. In a meeting of synthetic biologists interested in developing publishing criteria for the community, which problematically straddles scientific (publishing) and engineering (patenting and licensing) regimes of accreditation (see fn 44), one of Endy’s students suggested the community of *C. elegans* researchers, who, like Kohler’s “fly people,” converged upon a singular biological tool (the nematode *C. elegans*) and maintained a “tightly knit community” sustained by the free exchange of its totem, as a model of how successfully to engender a spirit of communalism (Chadarevian 2002).

Paul Rabinow characterizes synthetic biology as “a return of the organism...as an object of reformation” and “remediation” (2006). Perhaps. But the organism that is the object of synthetic biology is now beside the point, because the locus of the engineering impulse is being directed elsewhere.⁵¹ If the various genome projects of the 1990s sedimented the genome as the signature of a particular species, then synthetic biologists are building a heteroclit taxonomy of parts and devices that genetically draw together diverse species and socially draw together a community of practitioners devoted to and defined by their propagation. For example, the 2006 MIT iGEM team composed banana and wintergreen-scented bacteria, a biological system constituting genetic parts from three biological kingdoms: eubacteria (*E. coli*, *P. aeruginosa*), fungi (*S. cerevisiae*), and plants (*Petunia x hybrida*). Though they adhere to composition standards, the biotic things synthetic biologists freely exchange are composed of trans-species and multi-organismic genetic exchanges.

That is, BioBricks do not simply designate physical objects, but *relations* between biological and social kin and kinds — including the normative relations between synthetic biologists who publish BioBrick sequences online and store physical parts in the Registry’s freezer in Cambridge. Transgenic critters, such as strawberries bearing fish genes, have been troubling relatedness — species, lineage, consanguinity — for some time, as science studies scholars such as Sarah Franklin (2007) and Donna Haraway (1997) have noted. They “fit into

⁵¹ As Harvard synthetic biologist Pam Silver explains, “DNA is the fundamental unit of synthetic biology,” and that unit is defined not as mere substance, but as an encoding of *functions*: promoters, terminators, and introns (2009). Biology, on this view, is no longer an object of remediation, but a constellation of functions and implements. Indeed, synthetic biologists rarely talk about “organisms” as such — BioBrick parts are meant to be inserted not into “organisms,” or “species,” but in “chassis” — chassis like *E. coli*, *S. cerevisiae*, and *B. subtilis*. For the moment, the biological whole is a lot less interesting than the summing of its parts.

well-established taxonomic and evolutionary discourses and also blast widely understood senses of natural limit. What was distant and unrelated becomes intimate” (ibid: 56). Clicking through the online Registry of Standard Biological Parts is like touring a very strange menagerie: each BioBrick part is classified according to its *source*, but the logics under which those sources are cataloged vary: parts from yeast, petunias, snapdragons, bioluminescent marine bacteria, *Arabidopsis*, and fairy fan flowers appear under their Linnaean nomenclature. Parts assembled by *de novo* synthesis might list the name of the company that synthesized or sold them (e.g., Sigma Aldrich) or the published sequence from which they were synthesized (e.g. GenBank, Codon Devices), an informatic nomenclature. Parts borrowed from another researcher are sourced to the names of the researchers that gifted these parts, a kind of lab pedigree.⁵² At the top of each page, another link invites browsers to “view source.” Clicking on it leads to a page in which you can read and edit the website’s source code. Not source species, outsourced synthesis, or DNA as source code, but source as an invitation to edit and collaborate, pointing to the coupling of genetic relations to social relations that fall under the heading “Open Source.” The Registry’s URL suffix is, after all, mit.edu. Biotic and social modes of circulation and relatedness, and “natural” and “artificial” origins and exchanges, here hybridize.⁵³

⁵² A GFP protein, for example, bears this lineage: “This part was derived from the reporter device used by Elowitz’s repressilator. Elowitz obtained the GFP tagged sequence (*gfpmut3**) published by Andersen and coworkers to build the reporter device. Andersen constructed those GFP variants based on a *gfpmut3b* containing plasmid that was a gift from R. H. Valdivia” (http://partsregistry.org/wiki/index.php?title=Part:BBa_E0040).

⁵³ These haphazardly classified bits of DNA, RNA, and protein call to mind Borges’s “Chinese Encyclopedia,” the alogical taxonomy of creatures that inspired Foucault’s *Order of Things*. Foucault says of such taxonomies that they lead “to words and categories that lack all life and place, but are rooted in a ceremonial space, overburdened with complex figures, with tangled paths, strange places, secret passages, and unexpected communications” (1971: xix).

On the Registry, one can search for a part according to a number of criteria, such as its cellular function (promoters, ribosome binding sites, terminators), the desired final function of the designed system (parts assist in quorum sensing, cell death, odor production, chemotaxis, etc), the “chassis” in which that part will function, or the assembly standard to which the part conforms. These BioBrick parts are multiply about relations among things: they denote potential interspecies minglings, such that DNA from snapdragons may be ported into bacteria, they reference the social conventions by which standards are agreed upon, and through their free circulation, they coordinate practices among synthetic biologists who exchange and contribute still more parts. In a *New York Review of Books* essay on new biotechnologies, public intellectual Freeman Dyson compared such post-organismic circulation of genes to Open Source and free software movements:

As Homo sapiens domesticates the new biotechnology, we are reviving the ancient pre-Darwinian practice of horizontal gene transfer, moving genes easily from microbes to plants and animals, blurring the boundaries between species.... the rules of Open Source sharing will be extended from the exchange of software to the exchange of genes. Then the evolution of life will once again be communal, as it was in the good old days before separate species and intellectual property were invented (Dyson 2007: 6).

The comparison of genetic exchanges, couplings of petunias and *E. coli*, to the circulation of intellectual property and material artifacts alerts us to the fact that *species* not only marks stories of relatedness and exclusion, but is also about “filthy lucre, specie, gold, shit, filth, wealth” (Haraway 2003: 16). BioBricks, in their putative unmooring from species, betwixt and between source species and “chassis” organisms into which they are inserted, also promise other kinds of circulation, unbound (so the synthetic biological imagination claims) from intellectual

property regimes, drawing together not only diverse species in a post-organismic play, but also knitting together the synthetic biologists who argue about, assemble, modify, and share their parts.

In the following chapter, I turn to a growing community of “garage biohackers” who have appropriated the tools, techniques, and investments of synthetic biologists, including BioBrick parts, but moved them out of the lab and into their homes. Examining how such a movement has manifested itself alongside synthetic biology indicates that while the artifacts of constructive biology install and condition the socialities and practices of the researchers who make them, the uses of such objects are not dictated by the values and interests of their manufacturers. They can be appropriated as epistemic, technical, and social tools that serve altogether different ends.

Chapter 3. DIY Biology: Life Makes Itself at Home

In Spring 2008, I took a course in Advanced Topics in Synthetic Biology at MIT. In the fourth week of the course, the in-class assignment was to isolate DNA. The course materials focused on the ontology of DNA as a material thing, asking, “Is DNA (the physical material) inherently dangerous?” “Are there special places that DNA (the physical material) should be kept?” “Are there rules that can be enforced about its manipulation?” The introduction to the protocol continued:

If you've spent time in a research lab, there's a good chance you've worked with DNA there. Is that the only place DNA can be manipulated? What if the techniques and facilities for manipulating DNA were available to everyone? What if they already are? If you've never spent time working with DNA, then you're in for a treat. Today you'll isolate and purify some DNA using materials found in most any kitchen or garage.

The protocol was meant to be fun and accessible, with titles and subtitles like “Backyard Biology” and “Cookin’ up some DNA in your kitchen.” The pedagogical purpose of this assignment was unclear to me — the lesson was not *how* to isolate DNA, but more a demonstration that it could be done outside of a laboratory and without any specialized equipment. The protocol called for ingredients like wheat germ, liquid soap, meat tenderizer,

baking soda, and rubbing alcohol.¹ The follow-up questions asked students to consider three questions: “Who can hack computers and who can hack biology? Are there speed, safety, and training considerations? Do you expect to see garage biotechnologists in your lifetime? Do they already exist? Should they?” Since these questions were written already to assume their own answers,² this chapter begins with another question: What are the characteristics — technical and social, as well as accidental — of synthetic biology that have conditioned the rise of do-it-yourself (DIY) biology as a field that co-localizes and overlaps significantly with synthetic biology?

DIY (do-it-yourself) biology is a hobbyist science community (members refer to it in shorthand simply as “DIYbio” and to themselves as DIY biologists or biohackers).³ The story I tell in this chapter is not, strictly speaking, a story about biology, but it would not be possible without biology, either. It is a story about the surprising social formations that can assemble themselves around the artifacts of constructive biologies. Despite its institutional differences from synthetic biology, DIY biology, I argue, like synthetic biology, is predicated on a shared commitment to the idea that *understanding* biology will follow from *making* new biological things. However, the form that that making may take, who may engage in it, and where, is

¹ While neither the ingredients nor the instructions were specialized or required any particular skill, I nonetheless failed to isolate any wheat germ DNA. I misread the third and fourth steps, “3. Add one glob of liquid soap, 4. Mix a little bit every 1 minute for 5 minutes,” to mean that I should add 5 globs of soap at one minute intervals. While how much a “glob” is remains unclear, what did become obvious was my five globs were four too many. The liquid I stirred with increasing desperation was a foamy mess in which some DNA was no doubt present, but could not be extracted. More successful and enterprising students ran gel electrophoresis (their gel boxes were made of Legos) on their recovered samples.

² 1) Everyone! 2) Yes! 3) Yes! 4) Yes! 5) Yes!

³ I here refer to them as “biohackers” rather than DIY biologists, because “hacker” avoids clear distinctions between professionals and laypeople, whereas “DIY biologist” inadvertently confers on them an authority they do not possess.

currently under revision. With the Cambridge branch of DIY biology, I participated in kitchen laboratory experiments like isolating DNA using contact lens solution and rubbing alcohol, and running gel electrophoresis using 9-volt batteries, saline solution, and potato dextrose. Do-it-yourself biology is a science group for the amateur enthusiast, one that demands clever “hacks” by which the non-professional can skirt obstacles resulting from lack of access to professional-grade equipment, waste disposal services, regulated biological materials, and funding.

As its founders frame DIY biology, which arranges itself online as a constellation of local communities of amateurs, “We want to be the institution for the amateur, to provide access to the resources that you can’t get if you’re not in one of the traditional institutions like academia or industry: access to experts, like peers who can tell you how to get around that little problem. Or the literature, which unfortunately isn’t free. Gentle oversight.”⁴ Nearly everyone participating in the Cambridge branch of DIY biology has or is pursuing an undergraduate or graduate degree in a scientific field (although many of them in neither biology nor bioengineering), complicating, at least for me, what counts as being an “amateur.” Amateur science, it seems, has more to do with *where* experiments are done, and for what purposes, rather than who is doing them.

If synthetic biology proceeds by adhering to standardization, abstraction, and decoupling, then the principles of DIY biology are legible in its title: doing, it, yourself. Comparing themselves to computer hackers, for whom practical experience is valued as a route to political, social, and creative expression, they *do* science rather than, like other amateur activities like

⁴ <http://diybio.org/>

astronomy, observing it (Coleman 2004, Coleman and Golub 2008, Kelty 2008).⁵ *It* refers to the biological, whose status is currently under contest on account of synthetic biologists' efforts to streamline, standardize, and remake it. While biohackers claim to be trying to “democratize” biology, I contend that they are doing some deeper epistemological work here: the biological is not something cordoned off in labs, but is instead made quotidian, personal, apprehensible. This is biology as a mode of political action, in which practitioners frame doing biological research as a right rather than a privilege conferred with a PhD. I call this practice “political action” because it engages with issues of rights of access (to biological substances, tools, and techniques), legitimacy (who is a biologist?), public participation (what does it mean to be a member of science’s “public”?), and moral questions (who *should* do biology?). Biohackers address such questions to (and against) the reigning academic-industrial-governmental complex of life sciences research, including academic labs, private laboratories, and governmental organizations that regulate what it means to do biology safely and lawfully. And what counts as *yourself*, for these practitioners, distills in a biotic solution — conducting basic biological experiments on themselves, using their own tissues and genetic material, is a means of fashioning themselves as both biological subjects and political actors.

A community of “interested garagistas, academics, entrepreneurs, and other synthetic biology enthusiasts,” DIY biology started in Cambridge, Massachusetts (as, arguably, did

⁵ Anthropologists writing about Open Source software and hacker cultures have noted that Free and Open Source software offers a “*transposable* model for new legal possibilities composed of an aggregate of practices, licenses, social relationships, artifacts, and moral economies and, thus, enters a wider public debate on the limits of intellectual property primarily through a visible cultural praxis” (Coleman 2004: 509, emphasis in the original). This transposability of the Open Source model means that it has been adopted to a variety of ends, from pharmaceutical drug development, to computer software and hardware, to music, to politics, to consumer products like coffee and beer.

synthetic biology), but has since spread to include numerous satellite groups in cities such as London, New York, Seattle, and San Francisco [Figure 3.1]. Rather than enabling *large-scale* bioengineering, biohackers hope that synthetic biology's standard biological parts will instead facilitate *small-scale* amateur bioengineering. Biohackers do not question synthetic biologists' foundational equation of standardization to openness, nor do they ask whether biological matter

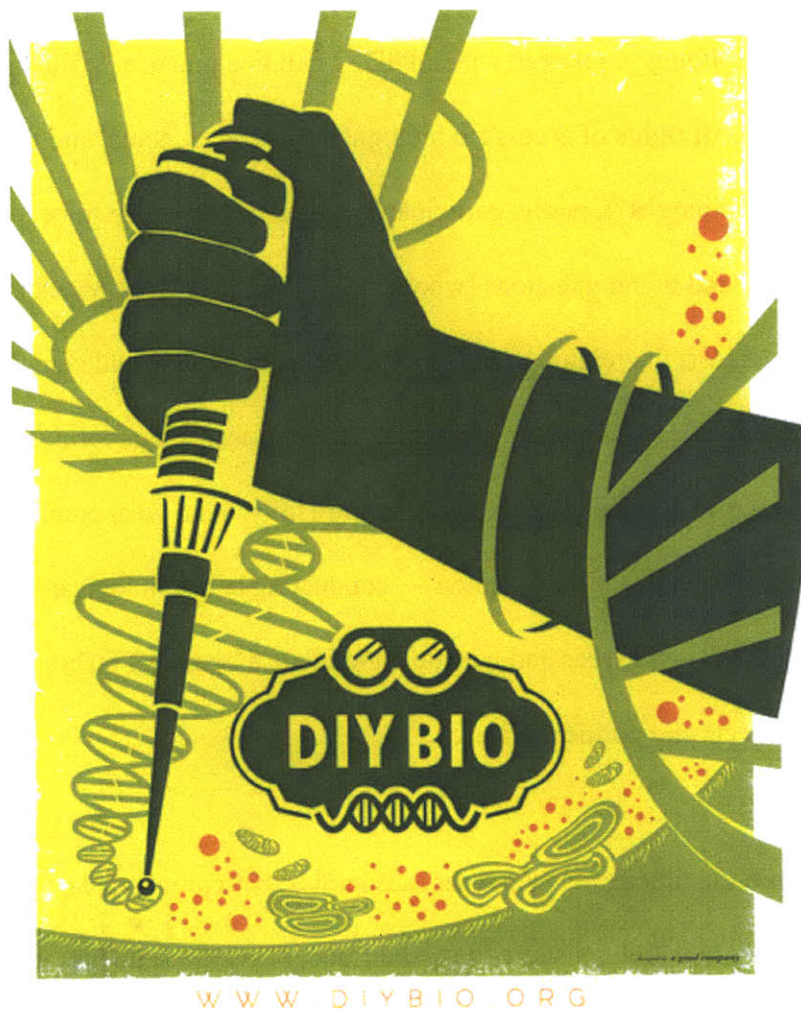


Figure 3.1. A hands-on approach to biology. Promotional poster for DIY biology, designed by A Good Company (TM).

is indeed standardizable or abstractable. While both popular newspaper accounts of DIY biology and biohackers themselves portray their group as off-grid and ground-up, DIY biology is enabled by and reliant upon the same concatenations of academic research, venture capital, intellectual property regimes, synthesis technologies, and security concerns that equip and authorize synthetic biology. Some of these biohackers are also affiliated with synthetic biology, having worked for synthetic biology labs or groups such as the Registry of Standard Biological Parts, or received degrees in bioengineering, biology, or computer engineering. However, many of them are not, and reject institutional and credentialed scientific vocation as a path to studying and engineering biology. Nonetheless, synthetic biology and DIY biology function symbiotically: DIY biology could not function without synthetic biology's infrastructure (DNA synthesis companies, standardized biological parts, freely accessible and collaboratively editable "wiki" lab notebooks, and cooperative synthetic biologists); synthetic biology may use DIY biology as an example of how standardization breeds openness.

DIY biology is enabled by the same metaphors that animate synthetic biology: that biology is a substrate that can be engineered and that biological parts should circulate freely, following Open Source models for software. Taking synthetic biologists' metaphor and running with it, biohackers suggest that if "life" may be rebuilt to function like a computer, then that computer can be hacked. The metaphors and "usable pasts" (Kelty 2008) that synthetic biologists invoke in describing their practice, in particular the claim that biological systems can be made to behave like electronic ones, are lively stories. If biology is something that may be engineered according to the same precepts applied to computers, as synthetic biologists claim,

then the socialities that emerged around computing in the last half century, such as electronics hobbyists, enthusiasts, and hackers, might find analogs in biological engineering. DIY biology is one such analog. Richard Doyle (1997), Donna Haraway (1997), Katherine Hayles (1999), Stefan Helmreich (1998), Lily Kay (2000), and Evelyn Fox Keller (1995, 2002) have all excavated how biology came to be articulated in a computational or cybernetic argot, in which organisms were complex networks of command, control, communication, and intelligence. But computing decamped from the Cold War when hackers pioneered timesharing and the personal computer, and though the computational metaphor has proven resilient in the life sciences, the form that metaphor takes is currently under renovation. Perhaps the appropriate figure for biology here is no longer the cyborg, but Open Source software: modifiable, shareable, collaboratively written, ubiquitous.⁶

The unorthodox younger sibling to synthetic biology, DIY biology is a hobbyist instantiation of a rapidly professionalizing field. In addition to the numerous people who participate in both communities, and the open source ethos shared by synthetic biologists and

⁶ Theoretical physicist and public intellectual Freeman Dyson has spoken and written about those he calls “practical biologists.” Summarizing these views in the *New York Review of Books* in 2007, Dyson predicted that “the domestication of biotechnology will dominate our lives during the next fifty years at least as much as the domestication of computers has dominated our lives during the previous fifty years.” He compared Big Biology like Monsanto to the big computers conceived by John von Neumann, and called for a biology that will be “small and domesticated” and “user-friendly.” This “domesticated biotechnology,” to use his coinage, “once it gets into the hands of housewives and children, will give us an explosion of diversity of new living creatures,” as children playing with biotech kits akin to computer games “will acquire an intimate feeling for the organisms they are growing” (Dyson 2007: 6-7). Dyson’s hope that children will gain “an intimate feeling for the organisms” evokes Evelyn Fox Keller’s characterization of geneticist Barbara McClintock’s “feeling for the organism,” borne of a keen discernment for and attention to her plants (1983). However, Dyson emphasized how a “hands-on” approach to biology will quell public anxieties about biotech aggravated by corporate entities like Monsanto, offering a more palpable and friendly biology in its stead. Such a prediction suggests that one of the potential outcomes of such biological experimentation will directly serve the ends of today’s corporate biotech interests rather than oppose them. Further, Dyson’s fantasy of practical biology reminds us that domesticating a technology does not necessarily translate into a more immediate understanding or processual relation to the object of that technology, biological or otherwise. The vision he painted of “user-friendly” biology hints at the last few decades of personal computing, in which a technology may become user-friendly and ubiquitous, but perhaps hackable by only a few.

amateur biologists, DIY biology recognizes the work of synthetic biology as foundational for making biology easier to engineer for those who are neither professional biologists nor engineers. Meredith Patterson, a biohacker who is making headway working at home to genetically modify bacteria to sense the presence of melamine (the contaminant that in 2007 was found in baby formulas and pet food), shared on an online forum how she understands the connection between the two groups: “One of my hopes is that the growth of synthetic biology will make the *language* of genetics something that people, especially young people — schoolkids, teenagers — grow up just as familiar with as algebra or how to balance a checkbook.” The question is, however, more than one of merely turning genetic engineering into something mediagenic and non-threatening. Biohackers see synthetic biology as a facilitating technology, a breakthrough that will transform biological engineering from a time-consuming ad hoc process prone to failure and intelligible only to a select priesthood into a relatively straightforward and foolproof bit of assembly. Synthetic biology, according to its practitioners, aims to transform bioengineering into an industrial mode of production, which, one synthetic biologist told me, would be recognizable by “the existence of standardized parts that users without intimate knowledge of every aspect of the system can use in a facile way.” Hewing to synthetic biology’s fantasy of standardized biological substance, DIYbiologists are just such users, or at least they hope to be. Adrian Mackenzie argues that “design” in synthetic biology does not simplify biological work, but instead might become “a vector of imagining pluralised participation in the making” (2010: 196). Standardizing parts does not standardize practice. Modes of engagement with biological things proliferate.

The metaphorical trafficking between computers and biologics that is rampant in synthetic biologists' talk not only analogizes things — computers to organisms — but also analogizes practices and socialities.⁷ If synthetic biologists picked up the comparison of computers to biology in order to apply principles drawn from engineering to biological things, then biohackers made a further transaction, modeling themselves upon socialities that developed around computing in the 1970s to produce an analogous sociality that works with the biological rather than the computational. I take DIY biology to be an example of what Kelty labels a “recursive public” (2008), in that the group mobilizes itself around producing the technical conditions of its own existence, which in this case is the right to de-institutionalize biological experimentation and manufacture.⁸ Taking seriously amateur groups like DIY Biology, I think, might be one way for science studies scholars to redefine the contours of scientific practice independent of the boundary work professional scientists do when policing the frontiers of legitimate science (Gieryn 1983, 1999). Instead of talking about what is *inside* and *outside* science, perhaps new forms of public participation in science suggest gradations and shades of scientific working and thinking.

While biohackers vocally espouse the principles of synthetic biology, I posit that what they mean by making is altogether different than synthetic biologists: *making* is less about following engineering principles than it is about tinkering and “making do,” by which I mean

⁷ The analogy of organisms as vital machines has a long history; see, e.g., Hopwood 1999; Keller 1995, 2002; Lenoir 1982; Pauly 1987.

⁸ Kelty's “recursive public” modifies Michael Warner's “public” to account for how people can organize themselves not only around shared discourses, but also shared practices that enable their existence as “a public.” Although DIY biology evinces characteristics of new social movements (Gerlach and Hine 1970, Melucci 1996), in that it is a loosely organized forum for collective action and shared practical knowledge, I avoid the term “movement” here because the group's ideologies and aims are not yet coherent nor organizing.

tactics whereby “commonplace objects... are encountered in unexpected or undefined, as well as apposite, ways” (Ewick and Silbey 1998: 186; for other theorizations of “making do,” consult De Certeau 1984, Garfinkel 1967, Nutch 1996). They do so, I argue, in order to destabilize what counts as legitimate scientific practice, to reframe biology as something constructible outside of professional laboratories, and to animate “biotechnical familiars” that reconcile biological objects (like standardized biological parts) and biological selves (the mundane biologies found in kitchens, gardens, and their own bodies). It is a constructive biology, in which biological substances and biological socialities are co-constructed.

Though they are not professional biologists, biohackers are part of the same technical and social infrastructures that make possible synthetic biology, and they use biological experimentation as a form of political action, arguing that non-biologists have a *right* to actively participate in and have access to biology. If what historian Philip Pauly (1987) called “the engineering ideal in biology” unfolded, in the twentieth century, within institutionally sanctioned spaces, then, in the twenty-first century we are witnessing synthetic biologists and self-described “biohackers” recasting the bioengineering project as malleable, open, and collaborative. I begin by mapping the hobbyist organization of “do-it-yourself” biologists, the work they do, where they do it, and what kind of projects they embark on as self-described amateurs and hackers. I next ask why DIY biology has manifested itself alongside synthetic biology, and what biotic ontology biohackers both presuppose and materialize. I then analyze ethnographic material from a single meeting of the Cambridge branch of DIY biology and the story of one of its members to examine how, using domestic, amateur, and even self-experimentation, biohackers reflexively

craft themselves as simultaneously biological actors and subjects. The dividend, I hope, will be a clarification of what the object of biology becomes when biological work gets done by non-biologists outside of circumscribed professional spaces, and when the biological project is (following synthetic biology) no longer simply analytic, but synthetic.

DO

A breakage in a chain of reasoning: just do it.

—RICHARD DOYLE, “LSDNA: Rhetoric, Consciousness Expansion, & the Emergence of Biotechnology” (2002)

The Oxford English Dictionary defines an amateur as “one who loves or is fond of; one who has a taste for anything” or “one who cultivates anything as a pastime, as distinguished from one who prosecutes it professionally; hence, sometimes used disparagingly, as = dabbler, or superficial student or worker.” *Amateur* comes from the Latin word for love, underlining the sense in which someone pursues an activity for pleasure rather than practical or monetary interest. When I write about biohackers as amateurs, I do not do so in any disparaging sense, but instead to underline the fact that these practitioners are fueled by passion and delight (Secord 2002). Unlike Victorian gentlemen amateurs, biohackers do not pursue or promote science as a path to personal improvement or refinement, but as a pleasure and a kind of political speech.

In this section, I unpack what biohackers mean by “doing,” clarifying how they draw upon amateur and hacker identities to make sense of their own practices both in relation to and against synthetic biology, describing the tactics by which they do their work, and where they do it. I submit that if synthetic biology is an imagining of biology, the *substance*, as it could be,

then DIY biology is an imagining of biology, the *discipline*, as it could be, or rather as it could be *undisciplined*. Disciplining, for Foucault, requires an “enclosure” in which bodies are partitioned and supervised, rendering cellular, organic, genetic, and combinatory bodies mechanical (1977). *Undisciplining* works both institutionally and bodily: locating work outside of supervisory enclosures (labs), yet enlisting the cellular, organic, and genetic bodies of biohackers in synthetic biology’s assertion that the biological can be made mechanical. While biohackers are unlikely to produce new biological knowledge, and will not garner the kind of authority afforded professional scientists, they are, by drawing biological techniques and tools out of dedicated laboratory spaces and pedagogical routines, *undisciplining* biology and arguing for rights of biological access and involvement outside of, or athwart, orthodox biology.

Months after I finished my fieldwork among the biohackers, I was interviewed by a journalist from *Le Monde* who wanted to write a compelling story about “garage biology.” After an hour of conversation, I became increasingly aware that the journalist was dissatisfied by what I had already told him about biohacking. Visibly disappointed, he asked whether there were some “real” amateurs with whom I could put him in touch. As he put it, could I give him the contact information of a car mechanic or a cowboy who did biological experiments in his free time? I apologetically informed him that I could not, as I had not yet had the pleasure of meeting a cowboy biohacker. Our meeting ended a few minutes later. The journalist’s frustration was revealing — DIY biology is decidedly a leisure activity of the sort pursued by members of the creative class and weekend warriors, comparable to birdwatching, or quilting, or automotive restoration, and it requires that the amateur have free time and money to set aside for

experimentation. Such a luxury no doubt excludes the car mechanics and cowboys of the world. Alec Resnick, an MIT dropout currently founding a community lab for “everyday experimentalists” in Cambridge, undermines distinctions between professional and amateur science, and simultaneously circumscribes experimentation as a leisure activity, when he explains, “You can be a waiter from 9-5, jam with your friends at night, and still call yourself a musician. But you can't do the same for science, yet.”⁹ Practicing science, on this view, is less vocation or avocation, and more recreation.

Science studies scholars who have written about amateur science so far have focused their attention on how non-scientists gain competence, proficiency, or credibility in discussing and deploying scientific facts, characterizing scientifically-engaged amateurs as “lay-experts” (Epstein 1998) or “amateur-experts” (Ellis and Waterton 2004). In appraising “orthodox” science, anthropologists and historians now attend to practice — what scientists *do*. Nonetheless, scholars examining how science is received by non-scientists still privilege the construction of semi-scientific personae through the deployment of scientific “facts” rather than studying performative communities of practice. Biohackers are not after facts so much as they are after artifacts — “doing” hobbyist biology, on their view, means building biological things rather than demonstrating facility with biological concepts or taxonomies.¹⁰ Historical accounts of “amateur” biology experimentation have surveyed scientific home-work in periods prior to the professionalization of biology, such that “the categories of ‘amateur’ and ‘professional’ have

⁹ For other accounts of how practitioners find time and space in which to pursue “serious leisure activities,” see Stalp 2006, Stebbins 1979.

¹⁰ For an interesting historical contrast, see Secord 1994, on early nineteenth-century working class amateur biologists who met in pubs to identify botanical specimens according to formal nomenclature.

been back-projected onto the nineteenth century” (Desmond 2001: 5; see also Alberti 2001, Barton 1998, Secord 1994). To be an amateur biologist in the current moment is to define your work athwart “Big Science” fields like synthetic biology (Galison and Hevly 1992), to work outside of it while poaching its resources and gadgetry, such as lab supplies and equipment. In short, amateur biologists want to *detrterritorialize* biological practice (Deleuze and Guattari 1983, 1987) by working outside of laboratories in order to argue for rights of access to biological materials and tools with which they might forward-engineer themselves as biohackers.

The motivation to move scientific work out of the laboratory and into the home is a historically productive one. Historians have shown that the professionalization of science is a relatively recent phenomenon transpiring in the late nineteenth century in lockstep with the inauguration of non-domestic laboratories. Indeed, before this time someone who undertook scientific experimentation in exchange for a wage by definition lacked authority and trustworthiness, as their observations may have been distorted by their financial stakes in the endeavor (Shapin 1989, Shapin and Schaffer 1985).¹¹ Central to the delineation of laboratory from domestic space is the division of craftwork or manual labor from conceptual labor.¹² However, as sociologist Richard Sennett explains, the last few centuries have not been kind to the amateur practitioner, whether in science or in craft practices: “the amateur gradually lost

¹¹ In her account of the Darwin-Sachs debate over gravitropism of root radicles, Soraya de Chadarevian demonstrates that the debate hinged on Sachs’s definition of what — and *where* — counted as legitimate scientific work: “Sachs redefined the standards of scientific work by turning the laboratory into a privileged place for access to ‘nature,’” which “implied the definition and exclusion of amateur practitioners as represented by the Darwins and the botanical work carried out in their family home” (1996: 18).

¹² Chadarevian points out that the technical virtuosity Sachs valued and identified with the laboratory was not uniformly esteemed in the sciences at the time; indeed the “strong emphasis on the craftsmanship of one’s own *métier* is relatively unusual in the history of nineteenth-century science. Chemistry, for instance, constituted itself as a scientific discipline in the period exactly by differentiating itself from its roots in craft and artisan traditions” (ibid 34).

ground, especially with the dawn of the Industrial Age — the amateur’s foraging curiosity seeming of lesser value than specialized knowledge” (2008: 246).

A laboratory is a professionally circumscribed space marked by dedicated machinery, a high division of labor, and legal imprimatur designating best practices, as well as the associated technical and manual virtuosity and observational discernment cultivated by apprenticing in such a social space. In scientific spaces, Peter Galison argues, “space is manipulated to concentrate the meanings crystallized around the science of a given time. It is through appropriation, adjacency, display, and symbolic allusion that space, knowledge and the construction of the architectural and scientific subject are deeply intertwined” (1999: 3). A non-professional space (either a private domestic space or a communal hacker workspace) bears none of the above qualities, and amateurs who work there risk any claim to authority, professionalism, or proficiency they might otherwise garner for their work, not to mention the “scientific subjecthood” working in a laboratory confers. Such a reversal of valuation is inevitable because, while the laboratory may possess the qualities listed above, more importantly, work done in the laboratory is invested with those qualities by dint of the social cache that the lab represents. This raises the question: why would an intelligent, capable, young person interested in doing scientific experimentation, a person who by accident of birth found him or herself in the U.S. middle class at the beginning of the twenty-first century, choose to join a loose-knit band of biohackers rather than take the institutional plunge, sign up for the GRE, and join the swelling ranks of graduate students in biological engineering? Because DIY folk do not want to be professional biologists or synthetic biologists. They want to petition, as non-scientists, for rights of access and

participation in synthetic biology and bioengineering. Said otherwise, DIY biology, in the contemporary political economy, amounts to rejecting an affirmation of “the visible display of the emblems of recognized expertise” as the sole outlet through which non-scientists may participate in biological experimentation and production (Shapin 1988: 404).

Mackenzie (Mac) Cowell, Jason Morrison, and Jason Bobe founded and helm the DIY biology online group, which currently includes around 850 members. As an undergraduate at Davidson College in North Carolina, Mac Cowell joined his school’s iGEM team in 2005. A few years later, he moved to Cambridge, where he talked his way into a job with the Registry of Standard Biological Parts, helping to organize subsequent iGEM competitions. What riveted Cowell was iGEM’s promise of democratizing the experience of biological experimentation by helping undergraduates learn how to engineer biological systems, work typically done only by scientists with a year or two of graduate school under their belts. Cowell quit working for the Registry in 2008, claiming that he “wasn’t learning new things” anymore, and sold his car to bankroll DIY biology. Bobe earned a bachelor’s degree in molecular biology at the University of Colorado, Boulder ten years ago, and now works for George Church on his Personal Genome Project at Harvard, which is enrolling a thousand volunteers willing to have their genomes published.

Bobe distinguishes between two strains of hobbyist science, which he characterizes as “exploratory” and “constructive,” while simultaneously undermining any distinction between the

two.¹³ Using the example of Katherine Aull, an MIT biological engineering alumna in her early 20s who is genotyping herself in her bedroom closet (about whom more later), he says, “she is doing both exploratory biology on her own DNA,” and “constructive biology in the sense that she’s really doing engineering and building and managing a lot of reagents.” Of Meredith Patterson, the biohacker (or, as she calls herself, “biopunk”) working to engineer melamine-detecting yogurt bacteria, Bobe says, “in order to do sensing, she’s doing constructive biology. So she’s doing exploratory biology through the constructive biology. So, you know, [the distinction between the two is] not really hard and fast.”¹⁴ The integration of “exploratory” (that is, experimental and observational) and “constructive” (i.e. engineering, building, and manufacturing) approaches to biology is, of course, beholden to synthetic biologists, who posit that engineering can itself be a form of biological exploration.

Cowell emphasizes the continuities he sees between the current crop of amateur biologists and examples of observational hobbyist science, like naturalism, bird-watching, and astronomy. So too, Meredith Patterson compares DIY biology to “birdwatching and cataloging trees”:

¹³ “Exploratory” and “constructive” approaches are not independent of one another, even in labs that synthetic biologists and biohackers might label “exploratory” — studying biology, to a greater or lesser extent, has always entailed making new biological entities, including organisms, as the literature on the history of model organisms demonstrates. For a review of this literature, see Chapter 1.

¹⁴ When talking about examples of what Bobe refers to as “constructive biology,” amateur biologists also are quick to naturalize their activities, placing them on a continuum with more commonplace and unremarkable examples of manipulating living things. Jason Kelly, one of the founders of Ginko Bioworks, a company that markets BioBrick parts to amateur biologists, asserts, “There’s no question in my mind that you can do biological engineering at home.... People have been gardening, breeding dogs and interacting with the living world for a long time.... There’s something compelling about it. So it’s the next step in that direction” (Moore 2009).

So I make that point about birdwatching and cataloging trees to remind people that biology is really, really big, and it's worthwhile for experts in small subfields to keep abreast of what's going on in other areas of the field, because our expertise can help other people and their expertise can help us. Between synthetic biology and birdwatching, absolutely. On the other hand, both DIY synthetic biology and birdwatching are biological endeavours, and a term like 'DIY biology' is broad enough to encompass both. Western culture has a long and exciting tradition of talented amateurs contributing to the progress of science, and I hope people remember that we're following in the steps of people like John James Audubon (who discovered and cataloged hundreds if not thousands of bird and mammalian species, expanding our understanding of North American biodiversity) as well as Edward Jenner, Jonas Salk, James Watson, Francis Crick, Kary Mullis and so on (Anderson 2009).

The difference is that bird watching and astronomy are practices of trained observation in which natural objects are identified and tracked by amateurs armed with textual and pictorial aids (Law and Lynch 1988), while DIY biology is a bird of a very different feather — its modus operandi is about making new things, building, tinkering, modifying, not merely observing. It is here that DIY biology appropriates from synthetic biology the language of hacking, which is by far the most culturally salient example of a community assembling and identifying itself as devoted to tinkering and building things outside of any clearly developed institutional script for accreditation or professionalization.

The DIY biology group communicates via a Google group listserve started in April 2008. Only a few dozen of all 850 members post regularly to the list. Many of the conversations on the list focus on developing the tools needed to conduct biology experiments at home, where to find cheap equipment, and how to build inexpensive versions of expensive lab equipment. For example, members offer one another advice on where to buy agar, a polysaccharide gelling agent commonly used as a medium for culturing microorganisms (you can find it in most Asian and

Indian groceries). They suggest to one another readily available alternatives to lysogeny broth, a liquid medium for growing bacteria (chicken broth being one adequate substitute). They also share information on the best outlets for cheap lab equipment. Scouring eBay, biohackers bid on gel boxes used to perform gel electrophoresis, shaker tables, vortexers, pipettes, and centrifuges at steeply reduced prices (\$500 gel boxes, for example, may now be bought online for \$9.95). Some prowl around biotech companies that have gone bankrupt, such as Codon Devices, “watching their dumpsters” for discarded lab equipment.¹⁵ Others more interested in tinkering cobble together equipment from odds and ends — assembling an incubator from a plastic cooler, a thermostat, and a light bulb, for example, or using an old turntable as an orbital shaker. If one of them notices a deal on equipment online, such as a DNA synthesizer on eBay for \$499, he will post it to the list. Making hay of the financial crisis, biohackers poach the leftovers of Big Biology.

The list is also a forum in which people working on home biological experimentation may seek advice when they run into problems, share successful protocols, post links to articles that they think will be of interest to other biohackers, and argue with one another about a range of topics, from how a hobbyist community can regulate best practices and lab safety among its members, to proper list etiquette and how members of the group should present themselves and formalize the aims of the group. As it stands, the group functions as an information clearinghouse and advocacy group for people who question that biological experimentation is the sole purview of those who are professionally trained and credentialed by accredited universities

¹⁵ Codon Devices was the DNA synthesis company founded by George Church and Drew Endy, which shut its doors in April 2009 after failing to raise enough venture capital to stay afloat. See Chapter 2.

and institutes. Biohackers want to master the technical laboratory skills inculcated in apprenticeship-based lab pedagogies (though not the myriad other oratorical and textual skills of self-presentation that successful scientists must learn), taking soil samples, isolating DNA, doing PCR, running gel electrophoresis, culturing bacteria and cell lines, and genetically modifying organisms.

The difference between DIY biology and synthetic biology might be compared to Claude Lévi-Strauss's characterization of engineering and bricolage, not least of all because members of the two groups adamantly refer to themselves as "engineers" and "tinkerers."¹⁶ The *bricoleur*, or tinkerer, speaks "through the medium of things" by combining diverse tasks and heterogeneous parts in order to build things, using the objects at hand in order to "make do" (1966: 21). Such objects are not dedicated to the project at hand, nor does the *bricoleur* order his projects according to the raw materials at his disposal. Instead, he draws upon heterogeneous materials that are the "contingent result of all the occasions there have been to renew or enrich the stock or to maintain it with the remains of previous constructions or destructions" (ibid: 17). A *bricoleur* is "someone who works with his hands and uses devious means compared to those of a craftsman" (ibid: 16-17). Comparing the approaches of *bricoleurs* to engineers, Lévi-Strauss claims that, "the engineer questions the universe, while the 'bricoleur' addresses himself to a collection of oddments left over from human endeavours, that is, only a sub-set of the culture" (ibid: 19).

¹⁶ The article published in *Le Monde*, the one whose author had asked that I direct him to "cowboy biohackers," appropriately was titled "Biohackers: Les Bricoleurs d'ADN" (Eudes 2009).

Such a definition certainly holds true for biohackers who “make do” with salad spinners for centrifuges and terrariums for thermocyclers, demonstrating, as Mac puts it, “how much science can be about duct tape and having a few screws in the right place” (Johnson 2009), and it further speaks to the way the biological figures in the imaginations of synthetic biologists and biohackers. As Rabinow (following Dagonnet) claims, bricolage is a biological impulse, or at least may be read as such by biologists and bioengineers who imagine their work to be part of a longer historical trajectory tracing from the Neolithic Revolution: “nature’s malleability,” he writes, “offers an ‘invitation’ to the artificial. Nature is a blind *bricoleur*, an elementary logic of combinations, yielding an infinity of potential differences” (1999a: 416). Biology, for synthetic biologists, is something that “offers an ‘invitation’ to the artificial.” Biohackers, on the other hand, aggressively position the biological as something commonplace, pervasive, and shared, which cannot be corralled within the laboratory, yet subscribe to synthetic biologists’ efforts to turn biology into an engineering substrate. Nonetheless, by adopting BioBricks as a facilitating technology for amateur biology, they tag biology as “a collection of oddments left over from human endeavours” (such as synthetic biologists’ BioBricks and discarded lab equipment), and a “sub-set of the culture” that may be co-opted to emergent tasks and locales.

DIY biology is a practical intervention into a pressing problem that many science studies scholars have already noted: that, theoretically and practically, the notion of “public understanding of science” is too tame to capture *doing* hobbyist science — any active or serious engagement with science that wants to go beyond a passive, downstream absorption of predigested knowledge, such as subscribing to *Scientific American* or watching NOVA (Irwin

and Michael 2003, Irwin and Wynne 1996, Wynne 1992). Further, “public understanding of science” shuts down any real appraisal of the “public” by treating it as a readymade entity. DIY biology, however, gets produced in the doing — by mobilizing around issues of access, experimentation, legitimacy, and the distribution of resources and information. Further, it actively organizes itself around a profound concern for the status of the biological as both an object of contests over authority and access (Who gets to work with biological material? Where? To what ends? Why is it okay to graft trees in your garden but not to splice a jellyfish gene into yogurt bacteria?) and an entity whose continual re-production conditions the existence of the amateur organization in the first place. In the next section, I appraise the status of biological substance as both object and subject of hobbyist practice.

IT

It may refer, not to any thing or person mentioned, but to a matter expressed or implied in a statement, or occupying the attention of the speaker.

—OED

What is the “expressed or implied” *it* to which biohackers refer when they claim to be “doing it themselves?” *It* is biology, but the object of biology, as I have argued in the previous chapter, is under contest in a moment in which its apprehension is predicated on its construction. “Once upon a time,” Richard Doyle recounts, the biological “*it* didn’t have a beginning, middle, or end. *It* was” (2002: 53). No more. The biological *it*, for biohackers, is both “life” as it gets made — that is, done and undone — as much as it refers to biological things, like BioBricks, which materialize synthetic biologists’ commitments to openness and modification. Biohackers

premise their work on the *it* that synthetic biologists are making, but they also locate biology in other locales — in their homes, in their grocery stores, in themselves. To sort out what *it* is, I first must excavate how synthetic biology spawned DIY biology.

The first physical meeting of DIY biology was held in May 2008 in the back room of a bar in Cambridge, a bar that, fittingly, is adjacent to a large biotech company. Around 25 people, ranging from MIT and Harvard professors and graduate students to high school students and science journalists, gathered to discuss a single question posed by Mac Cowell, the affable enthusiast at the helm of DIY biology: can molecular biology and bioengineering be a hobby? Cowell identified 1970s-era electronics hobbyists as kin when he said he wanted DIY biology to be “the Homebrew Computer Club of biology today.” The Homebrew Computer Club (HCC) was an amateur group started in Menlo Park, California in 1975, whose members included Apple founders Steve Jobs and Steve Wozniak.¹⁷ Piggybacking on breakthroughs in computer programming and electrical engineering, the Club ushered in the advent of home or personal computing (it was not, despite the way the folktale is narrated, just young guys with big ideas tinkering in garages). Personal computing, as it was forged by amateur groups like the Homebrew Computer Club, was a direct response to the monstrously big computing machines built during World War II and the following decades, one that sought to make computing an accessible, user-friendly, even domesticated, technology. So too, I argue that DIY biology is reacting to synthetic biologists’ project to build mass-produced biological systems to solve big-scale problems, like pharmaceuticals, biosensors, and biofuels. The comparison is, of course,

¹⁷ For a popular history of hackers and hacking, see Levy 1984.

pure American folklore, in which a little capital and a lot of geeky enthusiasm yields technological breakthroughs and piles of cash. Instead of Silicon Valley, call this story Carbon Valley. It orients biohackers precisely because of its hegemonic appeal, casting them as already the victors of the next big technological and commercial success story.¹⁸

The question that had been posed at the first meeting of the Homebrew Computer Club, as reported in the first issue of its newsletter, was: “What will people do with a computer in their home?” (Moore 1975). The question Cowell now posed to the crowd self-consciously echoed that earlier question: what will people do with *biology* in their home? The discussion that followed was lively, ranging from the suggestion that amateur biologists should work with model organisms easier to handle or visualize than *E. coli* or bacteriophage (such as moss), to possible causes for concern, such as the ambiguous legality of harboring bacterial and cell cultures outside of academic and industrial laboratories. The Homebrew Computer Club may not have single-handedly started the personal computing revolution, but the fact that biohackers draw upon this narrative as a myth from which to make sense of their own practice is nonetheless revealing. It suggests that dormant in their social imaginary is an analytic by which the democratization of biology is normatively good, and that the high road to such democratization requires bootstrapping upon the engineering ethos forged within synthetic biology.

¹⁸ Synthetic biologists also compare their work to the HCC, as when Drew Endy remarked, “When Apple got started, there was [sic] already lots of commodity electronics.... Woz [Apple founder Steve Wozniak] didn’t have to build his own power supply from stuff he dug up in the hills,” thereby intimating that genetic engineering was, by comparison, proceeding piecemeal by “digging up” extant genetic material with which to cobble together recombinant organisms (Parks 2007).

While the meeting could easily be read as a bit dubious or sub rosa, venerable MIT and Harvard professors were in attendance and talked animatedly about how to get amateur biology off the ground. Their presence suggested that DIY biology is not “outside” synthetic biology, but maintains an evolving symbiotic relationship to it.¹⁹ Tom Knight, storied hacker of MIT’s Computer Science and Artificial Intelligence Laboratory (Chapter 2), made suggestions veering between the practical and the mischievous; he went so far as to suggest that the group “subvert a well-respected organization like the Boy Scouts” to serve its ends.²⁰ Pam Silver, a professor and director of Harvard’s Systems Biology program, was supportive but circumspect, reminding those gathered three times over that “doing molecular biology is like an *apprenticeship* science” in which knowledge and skills are “passed down” from senior to junior molecular biologists working together in a traditional laboratory setting, and therefore might not lend itself to distributed autodidacticism.

Tom Knight, after attending this first DIY biology meeting, began posting regularly to the group’s listserv, offering advice based on his own self-taught knowledge of lab techniques on how to adapt certain procedures and tools for home use. He comments on topics ranging from the accuracy of home freezers to alternatives to pipettors to the myriad reasons why bacteria from your toilet should not be cultured. When he suggested to the group that they adopt halobacterium as a safe model organism, an argument broke out about whether it was truly

¹⁹ Drew Endy and Tom Knight contribute to the DIY biology listserv, as do their former students Jason Kelly, Reshma Shetty, and Austin Che, who after graduating from MIT started Ginkgo Bioworks with Barry Canton, another Synthetic Biology Working Group alumnus. Ginkgo is a start-up company that markets BioBrick parts and provides BioBrick assembly services and consulting.

²⁰ His reference to the Boy Scouts indicates that DIY biology trades on some of the imaginaries that animate the Boy Scouts: an American and masculine self-reliance, as well as good citizenship, cooperation, and responsibility. Note, also, that the annual iGEM competition is informally called “the jamboree,” like international Boy Scouts meetings.

“DIY” to order gel starter kits and other readymade products from biological supply companies. Jason, a student of Endy and Knight, pointed out that kits for constructing microcomputers were regularly advertised in electronics hobbyist magazines in the 1970s. The conversation devolved into a flame war in which members debated whether it would be more “DIY” to forge your own screws when building a gel box. Knight sniped rhetorically that “Real Men don’t use existing cells — they build their own. Mine their own salt, synthesize their own lipids, make their own DNA from sugar and phosphorus. We’ll put that Pasteur fellow in his place.” While this argument was a predictable bit of *reductio ad absurdum*, it suggests an ambiguity in what it means to “do it yourself,” especially in relation to appropriating and assembling the objects of synthetic biology for amateur biological experimentation. It also highlights that in constructing biological things, practitioners were also engaged in self-fashioning, here as rugged and capable “Real Men.”

While synthetic biology aims to develop an arsenal of characterized parts, which, synthetic biologists imagine, could potentially make biological engineering a less skill-laden endeavor, the DIY aesthetic assumes a *bricoleur*’s scavenging and creative use of found or built materials, some of which may well be BioBrick parts. The clean historical metaphors synthetic biologists deploy, which assume a linear progress in which materials and the structural relations of production become increasingly sophisticated and uniform, is insufficient for characterizing the sorts of labor practices biohackers propose. The notion of standards, and of standardized biological components, is capacious enough to encompass both mass production and at-home fabrication — standardized biological parts could enable assembly-line large scale manufacture

of synthetic biological systems, or be distributed among hobbyists who can get sequences of freely licensed BioBricks online and cheaply synthesize or amplify them. Hobbyist tinkering and industrialized manufacture are two modes of production that are not dialectically opposed in the twinned cultures of synthetic biology and DIY biology.

An impetus towards do-it-yourself biology was built into synthetic biology before the field had even really gained a foothold as a scientific community. In 2000, when synthetic biologist Drew Endy worked at the Molecular Sciences Institute, a non-profit lab dedicated to “open science” founded by Nobel laureate Sydney Brenner, he, Roger Brent, the current president of the Institute, and Rob Carlson, a self-described “garage biologist,” all cowrote a letter to DARPA requesting funds to work on what they called “Open Source Biology.” In the letter, the authors wrote, “considerable information is already available on how to manipulate and analyze DNA in the kitchen” (Carlson and Brent 2000). Citing the Amateur Scientist column of *Scientific American* written by Shawn Carlson, the three argued that many molecular biology lab techniques were growing increasingly comprehensible to non-PhDs, in part because of the glut of DNA kits on the market. They claimed that as DNA synthesis becomes faster and cheaper in coming years, “it will move from academic labs and large companies to smaller labs and businesses, perhaps ultimately to the home garage and kitchen” (ibid). Rob Carlson further forecasted:

Biological engineering will proceed from profession, to vocation, to avocation, because the availability of inexpensive, quality DNA sequencing and synthesis equipment will allow participation by anyone who wants to learn the details. In 2050, following the fine

tradition of hacking automobiles and computers, garage biology hacking will be well under way (Carlson 2001).

The fact that synthetic biologists were espousing garage biology before they even called themselves synthetic biologists reveals that nascent in both enterprises is a particular understanding of the biological — DIY biology’s “it” — as produced by and constitutive of social assemblages. Synthetic biologists agree upon standards for biological parts so that those standard parts might circulate smoothly and transparently among a growing number of researchers — that is, the community and the parts are mutually composed, as I argued in Chapter 2. While biohackers consider BioBricks simply to be an enabling technology, BioBricks, I would suggest, are also socially constitutive: the cluster of activities enabled by such standard parts — sharing, synthesizing, hacking, assembling — are the activities by which both synthetic biologists and biohackers not only assemble biological systems, but also assemble themselves. The “selves” biohackers here enact are liberal and autonomous actors for whom biological practice is a form of political speech, a speech arguing for rights of access to biological practice. The social and the biological are mutually constitutive. I return to this point in the following section.

DIY biology preceded the global financial crisis by a few months, but has come of age in its wake, which had a particularly damaging impact on synthetic biology labs, particularly those that had booted up within the previous five years and were still reliant on venture capital. In this sense, though the founders of synthetic biology had already imagined that standardized biological parts could empower “garage biology,” DIY biology would not have been possible had

it not built itself on the financial ruins of synthetic biology. Some biohackers have capitalized on the many industrial biology laboratories that either downsized, declared bankruptcy, or otherwise folded in 2009 by buying up their equipment; others (like Aull) are refugees of radical lab downsizing who must now conduct experiments in their own homes because there is simply nowhere else to do them.

A second reason DIY biology has latched onto synthetic biology's coattails relates to synthetic biology's origins in MIT's Computer Science and Artificial Intelligence Laboratory, a place storied for its ties to hacking. Indeed, MIT is credited as the fountainhead of hacking; even the term "hack" derives from MIT undergraduate pranks and stunts (Levy 1984). Mac Cowell openly models DIY biology on hacker practices, ending his public presentations with the slogan "real hackers write DNA," a sentiment echoed by the synthetic biologists who founded Ginkgo Bioworks after finishing doctoral degrees with Drew Endy and Tom Knight at MIT — the business cards they distribute label them "DNA hackers" and their phone number is HACK-DNA. At the 2007 MIT commencement, professor emeritus Charles Vest mentioned biohacking in his commencement speech, announcing that "Already the term 'biohacking' is heard along the Infinite Corridor [an indoor hallway connecting the east and west sides of the MIT campus]. 'Biohacking' ... just think about the significance of that term! It of course heralds the advent of synthetic biology, the fusion of engineering and biology to design and build novel biological functions and systems" (Vest 2007).²¹ Vest here conflates synthetic biology and DIY biology under the shared tag of "biohacking," demonstrating the extent to which both synthetic biology

²¹ <http://web.mit.edu/newsoffice/2007/comm-vestspeech-0608.html>

and DIY biology draw heavily upon the fantasy of the hacker, whose mythical origin and playground remains the MIT campus.

Cowell is quick to explain, both to me and to journalists, that hacking, as hackers use the term, does not necessarily have the alarming connotations it may hold outside of hacker communities. Hacking, Cowell insists, means “taking things apart and putting them back together in a new way that makes them better.... It’s not stealing bank accounts or anything like that. Hacking is good.”²² Indeed, at least on the DIY biology listserv, hacking is *so* good that members get into arguments about whether they are hackerly enough. A member named Daniel, who works by day as an aviation and electrical systems technician for the U.S. Army, suggested that members of DIY biology had not yet sufficiently learned the hacker ethos: “I honestly don’t think that biohackers (who lack a strong computer science hacking background) really grok hackerness yet.... But everyone wants to be a hacker, and the word has been corrupted so many times that few people — even those who actually are hackers — know what it means any more.”²³ Meredith Patterson responded to Daniel’s provocation by demonstrating that her hackerness was both academically and practically legitimate:

Well, I got my CS [computer science] hacking background and my biology background at the same time (started my internship at IDT [Integrated DNA Technologies] the same time I started my CS PhD), but I grokked hackerness when I was around, oh, five or six. Weekends in my dad’s workshop learning how to do carpentry and basic electronics, fix

²² Here, “goodness” means both a hacker’s intentions (i.e., “white hat” hackers) and is a moral claim, in which rights of access to and virtuoso modifications of biotic and technical systems are inherently valued.

²³ “Grok” is a science fiction term meaning “to understand completely.” For the etymology of this word, see Chapter 2, footnote 43.

cars, stuff like that. I don't know how many people who like to fix cars end up in biology, but the curiosity's the same.

Patterson's claim that "hackerness" is a disposition that can be cultivated through hands-on work, not just on computers or biology, but also on cars and carpentry, is a broad reading of what counts as "hacking." Christopher Kelty has argued that hacking temperaments express curiosity, virtuosity, and finding creative work-arounds to existing problems. However, he cautions that hackerness cannot be limited to a list of norms, but is negotiated through a recursive politics of inclusion: "You are a hacker when another hacker calls you a hacker" (2008: 36). This mutual recognition is precisely why arguments over "hackerness" can be so fraught on the listserv, and it is of an altogether different order than scientific identities, which are undergirded by dense infrastructures for maintaining legitimacy (professional organizations, pedagogical genealogies, formal pedagogies, and shared problems, theories, and techniques).

DIY biology is not the inevitable or predictable next step in synthetic biology, despite the claims of both synthetic biologists and biohackers to the contrary. Neither is it the economic crisis's answer to synthetic biology, a moment in which the life sciences are regrouping and rearranging themselves as pockets of venture capital wither and anxieties over bioterrorism are rife. Instead, it is symptomatic of synthetic biology — made possible by synthetic biology, but neither overdetermined by it nor answerable to it. Synthetic biology has established certain (social, technical, epistemological) structures that DIY biology exploits. Primary among these is the foundational fantasy of BioBrick parts. The analogy that biological substance is partible, characterizable, and standardizable in the same manner as mechanical and electronic components

is an analogy that frames all other aspects of both synthetic biology and DIY biology, including their shared commitments to openness, the structuring mythologies of the hacker, and the sorts of research programs they pursue. The “it” that is “occupying the attention” of biohackers is living substance, understood as both the biological commons of freely shared biological parts and the embodied biologies of amateur practitioners. As such, “it” always assumes the reflexive “yourself,” both the subject and object of experimental and constructive work, who is also in the making, a point to which I turn in the next section.

A month after the first DIY biology meeting, I arrived at Beta House, a communal workspace for hackers and software developers in Cambridge, early on a Thursday evening. This was the second meeting of DIY biology, and the first meeting in which members would attempt to dirty their hands with some biological experimentation. That night, the aim was a “DNA Extraction in the Kitchen,” following a protocol published in *Make* magazine, a quarterly about DIY and amateur technology projects that *The New York Times* described as “a throwback to an earlier time, before personal computers, to the prehistory of geekiness — the age of how-to manuals for clever boys, from the 1920’s to the 50’s” and as a “a grass-roots rebellion against consumer technology that they say stifles ingenuity by discouraging end-user modification” (Downes 2005). In the protocol, Shawn Carlson, founder of the Society for Amateur Scientists and a *Scientific American* columnist, played up the dramatic elements of DNA isolation, writing: “The properties of this massive molecule are so mysterious and

wondrous that most folks assume only the enlightened priesthood of laboratory biologists can extract and study it. Not so. In fact, anyone can extract, purify, and experiment with DNA at home” (Carlson 2007). A handful of people showed up, among them undergraduate and graduate students from the Boston area, recent graduates in the midst of founding startup companies, and one transhumanist.²⁴

As people filtered into Beta House, Cowell put out a plastic collection jar on the kitchen island to offset the cost of beer and pizza, and to help fund a hoped-for future centrifuge. Conversation early in the night centered on finding practical tools with which to do DIY biology: what kind of model organism could hobbyists work with? One member suggested yeast as a model organism because it is inexpensive, easily acquirable, and unlikely to raise the hackles of the FBI, given its long history of home cultivation for baking bread and brewing beer.²⁵ A few people talked about building a cheap centrifuge. They had already tried tying a sample to the end of a piece of string and whirling it around, a technique with which they could reach a centripetal acceleration of 60g, but which had the drawback of quickly becoming fatiguing. Someone else had tried hacking together a centrifuge using a blender motor, taping up the blades before attaching samples to them. Everyone in attendance that night, except me and Cowell’s girlfriend, were young white men in their twenties. The image of the hacker is overwhelmingly

²⁴ Transhumanists are interested in technically augmenting or supplementing human bodies to maintain consciousness beyond the human lifespan, for example, by uploading consciousness online or via cryopreservation. Transhumanists maintain an active presence on the DIY biology listserv.

²⁵ The FBI’s Weapons of Mass Destruction Directorate is currently piloting a Biological Sciences Outreach Program (nicknamed “FBIO”), and sends agents to both synthetic biology events (including iGEM) and DIY biology meetings and workshops. A supervisory special agent in the program, speaking at a biosecurity conference in Washington DC in March 2010, cited the “distinctly different cultures” of life scientists and law enforcement as a primary challenge for agents in his program.

coded as male, straight, and white (although increasingly inclusive towards Asians and South Asians), a persona which almost certainly discourages or alienates women and GLBT people from cultivating hacker personae or gaining a foothold in the community.²⁶ Hacker mythologies further “the notion that programming and computing” are coded as “masculine activities” (Light 1999). Despite the intervening five decades, “the age of how-to manuals for clever boys” persists.

Before beginning that night’s experiment, we reviewed the DNA isolation protocol over beers, perched on bar seats around a central island that separated the kitchen from the clusters of desks and couches crowding the work area. Cowell drew a flowchart of the protocol on a whiteboard, we gathered together the necessary materials, and set to work. To begin, we mixed a buffer solution of distilled water, salt, baking soda, and dish soap, which is used to lyse open cells, releasing the DNA into solution. As a source of DNA, some people had brought fresh fruit, chopping up and grinding apples into a puree. Others ground up oatmeal, and I worked with a young software hacker from a nearby university to extract human DNA: we both chewed lightly on the inside of our cheeks before spitting into a plastic cup. Everyone had a ready source of biological material on hand, whether it was the leftover fruit carried in backpacks or messenger bags, the toppings on the pizza Mac had ordered to sustain the apprentice biohackers while they worked, or the bodies of the hackers themselves.

²⁶ Nonetheless, a few women are becoming increasingly vocal and active members of the DIY biology community; notable among them are Patterson and Aull.

Once everyone had minced, pulverized, or chewed their sources of DNA into viscous solutions, we added a few drops of contact lens solution to the buffer, which broke up the proteins that had burst from the cells with the DNA. We put this solution on ice to keep the DNA from degrading too quickly. One attendee had stolen a handful of plastic Corning test tubes from a lab at Harvard, and we loaded three tubes with apple, oatmeal, and human samples, then added 2 teaspoons of buffer to each tube, shaking to mix. The next step was to separate the liquid in the sample from the solid matter. If we had a working centrifuge, this would have been the point in the protocol to use it, but we did not, so instead we used paper coffee filters. The final step was to precipitate the DNA out of the buffer solution, which is accomplished by dropping the salt concentration using alcohol. We started by using isopropyl alcohol, which we pipetted out of its bottle with a plastic drinking straw, dribbling it along the inside edge of each test tube so that it settled in a layer above the buffer. At the interface between the buffer and the alcohol, the DNA precipitated out of solution, as a cloudy tangle of white filaments floating in the rubbing alcohol [Figure 3.2].

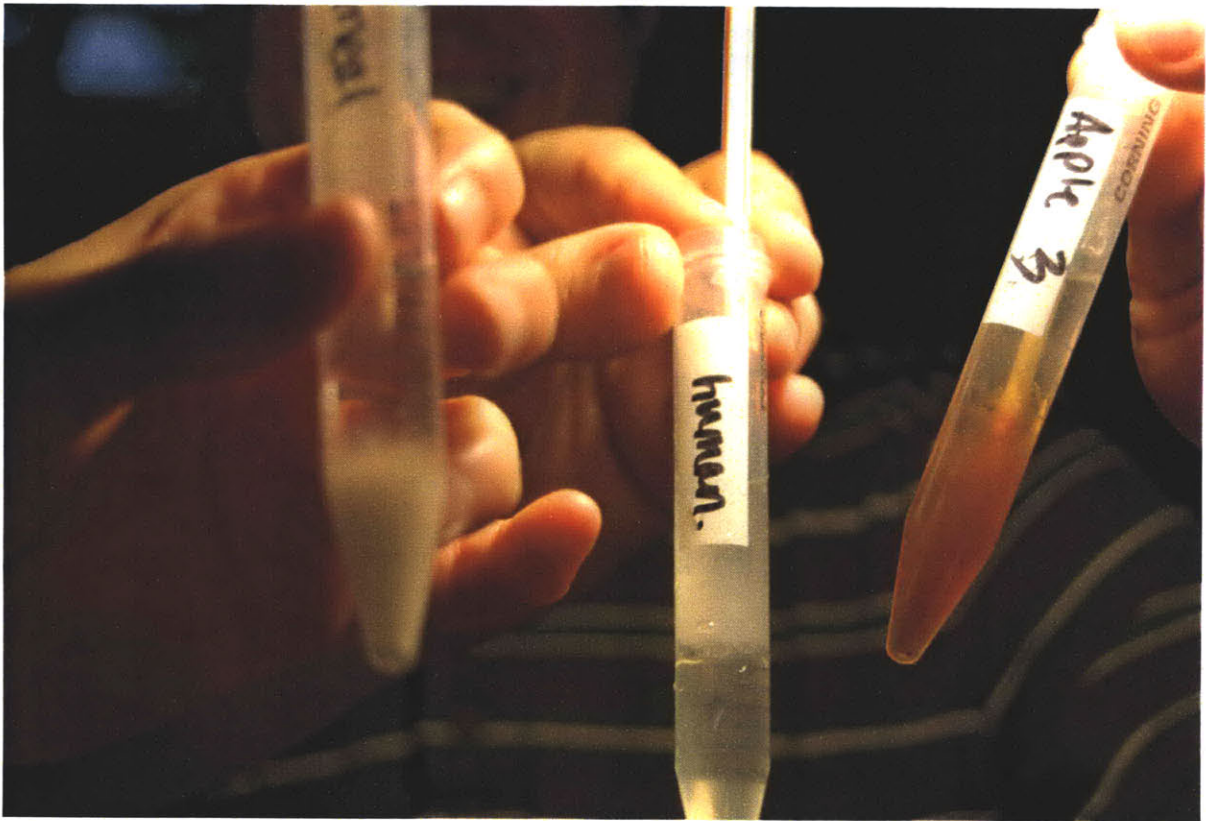


Figure 3.2. Isolated samples of apple, oatmeal, and human DNA, extracted during the second DIY biology meeting, June 2008. Some (but not all) of the human DNA is the author's own.

Photo: Mackenzie Cowell.

When the DNA became visible, there was a flurry of photographs, as people took out iPhones and digital cameras and photographed one another staring into test tubes held up to the light, aping the scientist's headshot so common in newspapers and glossy magazines. People were grinning, excited; some laughed in apparent pleasure and wonderment. Originally the plan had been to immediately start working on gel electrophoresis of our isolated DNA, but the protocol took longer than anticipated and it was getting late, so the electrophoresis was postponed until the next meeting. We dipped toothpicks taped to the ends of straws into our test tubes, and the suspended DNA clung snottily to the end of the toothpick. We then dropped the

toothpick, with its attached DNA globule, into a second tube of isopropyl alcohol, which could then chill indefinitely in the freezer. Cowell was feeling playful, and mixed up what he called a “DNA shot” — he poured some leftover buffer and pureed oatmeal into a shot glass and dribbled some chilled Bombay Sapphire gin along the glass’s inside edge, so that the oatmeal DNA fell out of solution at the interface. With an impish grin, he then tilted his head back and knocked back the shot, screwing up his face at what I imagine tasted like soapy sludge. A few of the others followed suit, offering me a shot as well. I declined. The combination of salt and soap and oatmeal, despite being tempered by gin, was singularly unappealing to me.

YOURSELF

Surrounded by a membrane, the cell lives less in itself or for itself as at home with itself.

—MICHEL SERRES, *Atlas* (1994)²⁷

What was being manifested in the test tubes when this fibrous genetic gloop coagulated out of solution? What sort of DNA had materialized: was it the rhetorical “magnetic tape” or “code” containing the “secret of life” (Keller 2002: 140)? The linguistic, cryptographic, or mystical “Word” or “Book of Life” (Kay 2000)? An organismic “blueprint” (Oyama 2000 [1985]), a “code-script” (Schrödinger 1944), an “artificial intelligence” (Adams 1989, quoted in Doyle 1997) or “machine language program” (Helmreich 1998)? Was it DNA as information, map, “code of codes,” “master molecule,” or any of the other hoary metaphors with which nucleic acids have been freighted?

²⁷ Translation by Steven Connor, quoted in “Topologies: Michel Serres and the Shapes of Thought.” Paper delivered at the “Literature and Science” conference, Ascoli Piceno, Italy, 20-22 May 2002.

I am sure that many of the biohackers in attendance that night had been marinated in such rhetorics, but that is not why they were laughing. Instead, this sounded more like a laughter of recognition, the sort of excitability Natasha Myers diagnoses among life scientists who recognize an “*affective response-ability* in [the] participating bodies” of biologists and the biological substances with which they work (2007: 258). I think their laughter also reverberated from a disconcertingly reflexive subjecthood, predicated upon what critics of biology alternately have called the “genetic self” (Novas and Rose 2000), “biosociality” (Rabinow 1992), “biotechnological individualism” (Heath, Rapp, and Taussig 2003, Rapp, Heath, and Taussig 2001), and “genetic citizenship” (Rapp 1999), in which identity, selfhood, and relatedness is conflated with genetic material. The reflexive pronoun in “do it yourself” is a form of address in which “you” is both the subject and object of the *doing*. In my case, I was very much both subject and object — one of the tubes being held up to the light contained my own DNA. What had precipitated in solution was a reflexive mode of self-experimentation, the inauguration of a biological self in which biohackers recognized themselves as both biohackers (the *doing* subjects) and also eminently and materially biological (the direct object of experimental action).²⁸

An example will clarify this point. Katherine (Kay) Aull is a 24-year old woman who is enthusiastic about DIY biology. I first met Aull when she was a sophomore in biological engineering at MIT, while I was observing an undergraduate synthetic biology laboratory.

²⁸ Richard Doyle has written of other, more psychedelic attempts at DNA ingestion, suggesting that “taking DNA” entails a “fundamentally *pragmatic* rather than *semantic* relation to the ‘information’ of DNA, more recipe than message” (2002: 158).

Dressed in sweatpants and a floral shirt, she described herself to me as a “dork” and actively cultivated among her peers her geek persona, bragging, for example, about subsisting solely on a diet of PopTarts and working for days without sleep. After graduating from MIT in 2008, Aull got a job as a research associate at Endy and Church’s company, Codon Devices, but lost her job during layoffs shortly before the company closed in 2009.²⁹ Having kept some kind of lab set up in her home since she was in middle school, in 2008, she built a makeshift bioengineering laboratory in her bedroom closet, hoping to compete in the “Mad Science” competition hosted by a popular science fiction website. The competition’s call read: “we want biology to be brazen. We’re rooting for mad scientists with homebrew closet labs, grassroots geneticists, and garage genome hackers — because they’re the researchers most likely to change the world.”³⁰ The subversive — and potentially lucrative — nature of keeping a workspace in one’s home is a mythology already carefully trodden by previous generations of computer hackers and programmers, and is, as I have already suggested, an orienting trope for the current crop of biohackers. As a *Boston Globe* journalist posed the question, “If hobbyists can hack computers together in their garages to create companies like Apple and Hewlett Packard, why not practice genetics in your closet?” (Johnson 2009).

²⁹ Evaluating why she thought Codon did not work, Aull chalked it up to the limits of synthetic biology’s capabilities compared to what Codon had promised. “The basic postmortem analysis,” she wrote, is that “we’re not good enough at synthetic biology yet. Ultimately, the dream was to build a ‘biofab’ — you have an idea for some biological widget, we have experts that can build it, and more efficiently than you can. Turns out that’s hard. We’re not good enough — there’s too much luck and black magic involved in getting each instance to work, and the benefits of scale get lost” (Interview with author).

³⁰ <http://io9.com/5049810/announcing-the-winners-of-the-io9-mad-science-contest>



Figure 3.3. Katherine Aull’s home laboratory, in her bedroom closet.
Photo: Katherine Aull.

Kay’s lab, which she describes as “a fully functional genetic engineering research lab” that cost “about a thousand dollars to put together,” includes a thermocycler she bought on eBay for \$59, a centrifuge, and an incubator made out of a styrofoam cooler and a heating element [Figure 3.3]. Recently, Kay used her lab to conduct a genetic test on herself. Her father had recently been diagnosed with hemochromatosis, a treatable but incurable heritable disease

causing iron to accumulate in the blood. Rather than paying for a genetic test to find out whether she inherited his condition, Kay swabbed her cheek, used her thermocycler to PCR the sample, and ran a gel electrophoresis on the resulting snippets of DNA.

Because she does not have the same filtration and waste disposal systems that are in place in commercial and academic laboratories, Kay is dedicated to using safe alternatives to common laboratory chemicals: she substitutes methylene blue, an aquarium fungicide, for ethidium bromide, a carcinogenic fluorescent tag typically used in gel electrophoresis. As she described it to other members of the online listserve, the process is “a lot like cooking, or cleaning, or working on your car.” Kay’s first test indicated that she does carry both genes for hemochromatosis. Estranged from her mother for nearly two decades, Kay now possesses relevant genetic information about her mother, and must decide whether to contact her in order to reveal it. Kay’s relationship to her own biology, her enactment of a liberal identity capable of self-action, and her appraisal of her own genome as a biotechnical familiar that divulges her kinship to people with whom she may feel *unfamiliar*, all come into focus in Kay’s decision to not only do it herself, but to do it *on* herself.

The figure of the closet evokes the alchemical closet, with its whiff of hermetic secrecy and craftsmanship to which the modern conception of the laboratory is often contrasted (Galison and Thompson 1999). It also implies the semantics of being “closeted,” which, since the inception of the gay rights movement, has come to stand for an altogether different sort of self-experimentation than the kind Kay conducts — the closet, as queer theorists remind us, is thickly

laden with politics of identity and self-fashioning, privacy, disclosure, social responsibility, inclusion and exclusion, as well as understandings of what is natural and unnatural (Butler 1991, Sedgwick 2008 [1990]), all of which are also interleaved in DIY biology. The two notions of the closet are linked by a shared concern for identity construction; Kay's genetic engineering closet and the queer closet are both spaces in which the closeted may forge an identity protected from the attentions of social norms and mores. Kay may then come out of her closet with an understanding of herself, as her father's daughter, as the inheritor of her mother's genetic legacy, as someone at future risk for hemochromatosis. Refracting such domestic experimentations through the lens of queer studies and identity politics brings to the fore not only the work of making selves, but also the power dynamics at play for biohackers, for whom closets, kitchens, garages, and other domestic spaces are, to quote Michael Warner, arenas in which "the strategic separation of mutually implied knowledges — secret knowledge, superior insight, disavowal, science, coded knowledge, open secrets... is a medium of domination not reducible to other forms of domination" (1993: xiv).

In an interview with journalists from *The Boston Globe*, Aull explained her reasons for doing biology experiments in her home, saying: "For so many people, biology is something scary that takes place in a lab.... This shows people it's understandable, and part of your life.... You can do it with basic kitchen equipment" (Johnson 2009). There is more to what Aull is up to than, as she claims, simply desensitizing the public to biological experimentation and manufacture. By allowing her own genome to be the locus of her action upon herself, Aull reframes the object of experimental action as not the isolated, pure, hothouse biology of the laboratory, but the

quotidian and intensely personal biology with which we engage, knowingly or not, on a daily basis.

What I claim is brewing among biohackers is a different sort of relation to biology, both biological stuff and biological practice. Biology, for Aull, is not only the kind of work she did in labs at MIT or companies like Codon, but also something personal, and not just because she has begun experimenting on herself. When Kay talks about biology, she here means biology as a set of protocols, rather than biological stuff. Note her wording in the above quote: biology is something, she insists, that you can “*do...with basic kitchen equipment.*” She and other biohackers are adamantly rejecting a consumer model of biology, in which biological parts are licensed and sold, and genetic tests are ordered, paid for, and received neatly, perhaps prettified with a bit of genetic counseling. Instead, they espouse biology as something to be made, hacked, taken apart, put back together, and even, in the case of Cowell’s DNA shots, ingested. This messy engagement with biological stuff and practice is about refusing the articulations of experimentation and fabrication, analysis and synthesis, induction and production, endemic in biology and bioengineering disciplines. To sum up: synthetic biologists make biological artifacts, and biological artifacts make synthetic biologists. However, the forms of biotic, economic, and social relatedness that inhere in BioBricks also enable biohackers, by appropriating and deterritorializing these biological things, to argue for their right also to use them — and other biotic things — as a precondition for their own existence as a group working athwart professional biology.

CONCLUSION

Following Kaushik Sunder Rajan's use of the *symptom*, I have taken DIY biology to be "a subsumed, incongruent, evolving component" of the convergence of making and knowing in the contemporary life sciences (2006). One cannot make sense of synthetic biology without also attending to its disqualified and illegitimate kin, which, as I have shown, was already cocooned within the synthetic biology project back in 2000. "The engineering ideal in biology" has migrated into new domestic spaces, and into new configurations of authority, subjectivity, and practice. This transformation of the engineering ideal, I have argued, might recast biological substance as something that is not solely under the guardianship and prerogative of accredited professionals.

To end, let me return to a question which, following Landecker (2007), I asked in the previous chapter: what does it mean to "be biological" in the current moment? The answer is that, ironically, attempts to standardize biological substance have, by yoking analysis to synthesis, yielded a much more capacious sense of the biological, in which the biological is something always under construction, something both ubiquitous and quotidian, not to mention hackable. DIY biology does not reformat or significantly impact the biosciences, and I doubt it ever will. However, the phenomenon of biohacking suggest that when constructive biologies build social norms, values, and practices into biological things, those artifacts are not fixed, but can travel and be adapted into new patterns of practice, professional (il)legitimacy, affective engagement, labor, recreation, and self-making. Biohackers who perform DNA extractions and gel electrophoresis on commonplace organisms such as tomatoes, kiwis, peas, strawberries,

onions, bananas, and humans are animating a biotechnical familiar, officiating in an act of transubstantiation by which the nucleic acid common to all living things and readily available in any domestic setting is converted from something natural and commonplace into something biotechnical. Their assertion, I suspect, is that the biotechnical object should have already been a biological familiar all along.

In the next chapter, I turn to an altogether different sort of amateur biological practice, the Hyperbolic Crochet Coral Reef. Whereas biohackers are captivated by biological substance, the women crafting the Hyperbolic Crochet Coral Reef render coralline forms in abiotic media, such as yarn and plastic, in order to gain a practical understanding of biological concepts such as evolution and morphology. What biohackers and coral reef crafters share, however, is a commitment to domestic hands-on work as a mode of political and self-expression.

Chapter 4.

The Hyperbolic Crochet Coral Reef: Evolutionary Yarns in Seahorse Valley

Tissue, textile, and fabric provide excellent models of knowledge, excellent quasi-abstract objects, primal varieties:
the world is a mass of laundry.

—MICHEL SERRES, *Les Cinq Sens* (1998)

Housekeeping, the art of the infinite, is no game for amateurs.

—URSULA K. LE GUIN, “Sur” (1982)

Making a lung with a piece of esophagus sounds very much like making a skirt with a piece of Granny's curtain.

—FRANÇOIS JACOB *The Possible and the Actual* (1982)

INTRODUCTION: A VISIT TO SEAHORSE VALLEY

Margaret Wertheim, a well-known science communicator, writer, and co-founder of the Institute For Figuring, invited me to the sprawling American Craftsman-style home she shares with her twin sister, Christine, on an overcast and rainy morning in late November 2008. The Institute For Figuring (IFF) is headquartered in the Wertheims' home, out of which the twins organize workshops and exhibitions and write about a web of mathematical and aesthetic activities that the women classify as “figuring.”¹ The IFF is, according to its directors,

dedicated to enhancing the public understanding of figures and figuring techniques. From the physics of snowflakes and the hyperbolic geometry of sea slugs, to the mathematics of paper folding and graphical models of the human mind, the Institute takes as its purview a complex ecology of figuring.

The Institute For Figuring website reports that IFF Headquarters “does not yet have a physical space, but [a]... permanent location in the conceptual landscape” known as the Mandelbrot set, a

¹ The acronym IFF also abbreviates the logical biconditional “if and only if,” (i.e., a necessary and sufficient condition) in mathematics and logic notation.

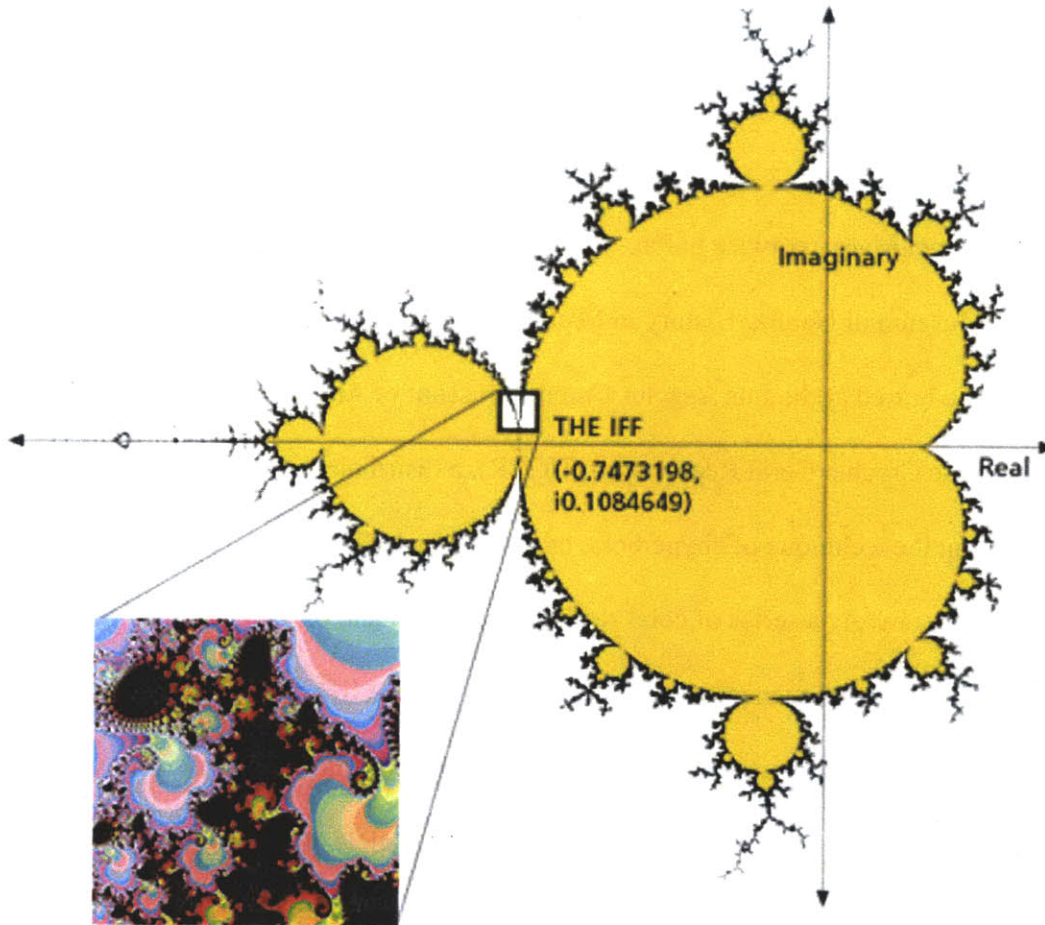


Figure 4.1. “IFF Mandelbrot set location: (-0.7473198, i0.1084649) with detail (color inset.)”

Source: <http://www.theiff.org/about/mset.html>

fractal mathematical space on the plane of intersection of the real and imaginary numbers, obtained by the quadratic equation $z_{(n+1)} = z_n^2 + C$. The IFF, the Wertheims say, sits at coordinates -0.7473198, i0.1084649, in a deep furrow between the “head” and “shoulder” of the Mandelbrot Set [Figure 4.1]. This neighborhood of the set is colloquially known by mathematicians as the “Seahorse Valley,” because it is composed of clusters of biologically

suggestive stalks and fronds.² In the lived world, Seahorse Valley roughly maps onto a quiet cul-de-sac in Highland Park, a predominantly Hispanic district of northeast Los Angeles.

I had met Margaret twice before, once at a lecture she had given six months prior at the American Museum of Natural History in Manhattan, and again a few weeks earlier at a workshop she hosted at the Los Angeles County Museum of Art. I wanted to learn more about the Hyperbolic Crochet Coral Reef project (HCCR), a distributed venture of thousands of women who are using the technique of “hyperbolic crochet” invented by geometer Daina Taimina to fabricate cooperatively a series of coral reefs made of yarn and plastic, with the intention of drawing attention to the menace climate change poses to the Great Barrier and other coral reefs. Crochet is a fiber arts technique that uses a single hooked needle to loop together yarn to produce a fabric. Hyperbolic crochet is a method of fabricating models of hyperbolic geometry, a kind of non-Euclidean geometric space characterized by a constant negative curvature (spheres, in contrast, have constant positive curvature). Many marine organisms have evolved to embody hyperbolic geometry; it affords them a maximum surface area with which to filter feed in a minimal volume.

That crochet is the best technique for modeling hyperbolic geometry, and that coral reefs embody this same geometry, makes the Hyperbolic Crochet Coral Reef project, which Wertheim describes as a “giant, ongoing, evolutionary, fancywork experiment” (unpublished manuscript)

² Margaret has written two letters to Benoit Mandelbrot requesting his permission to draft a 99-year lease on Seahorse Valley (she does not wish to own this territory because, she says, as an Australian she is wary of colonialism, not wanting “to repeat the sins of Australians colonizing aboriginal lands”). His secretary responded to her first letter by informing her that mathematical objects are in the public domain; her second request remains unanswered.

and “a wormhole into an alternate universe of creative feminine energy” (Yury 2009) (because contributors are overwhelmingly women, and crochet is a traditionally feminine-identified skill), seem somewhat less peculiar than it does at first gloss.³ Coral reefs have long proven themselves good to think with. In Darwin’s first monograph, conceived during his travels on the *Beagle*, the naturalist outlined many of his later theories while meditating upon coral reefs:

In an old-standing reef, the corals, which are so different in kind on different parts of it, are probably all adapted to the stations they occupy, and hold their places, like other organic beings, by a struggle one with another, and with external nature; hence we may infer that their growth would generally be slow, except under peculiarly favourable circumstances (1842: 76).

It is, then, altogether fitting that coral reefs, which have more recently made headlines as sentinels of climatological crisis, now figure as object and artifact of a project that melds biological and evolutionary apprehensions with ecological activism. The Hyperbolic Crochet Coral Reef project is not a scientific venture; it is a distributed craft project that draws on a mathematical modeling technique to explore biological theories. Nonetheless, it is one place in which people are telling stories about life by simulating biological forms in non-biological media, and I thus recognize it as an example of “constructive biology,” in which making things is an avenue by which to learn about biology.

³ Daina Taimina, the mathematician who invented hyperbolic crochet as a mathematical modeling technique, explains that using yarn (rather than paper, out of which earlier models were made) makes models that are sturdy and can be physically manipulated. She “saw that this [mathematical] graph [of hyperbolic geometry] can be a crochet pattern where each line segment denotes a stitch. And there it was -- the pattern for the hyperbolic plane. All that was left was to try it. First, I tried to knit since I am an avid knitter. But the number of stitches on the needles soon became unmanageable, and I was afraid that as soon as I accidentally lost a stitch, the whole work would unravel. So, I decided to crochet because it gives more freedom in space and I had to deal only with one stitch at a time” (2009: 20-21).

If coral is a fitting organism, then crochet, a traditionally feminine craft, is a fitting technique, because, as I will argue, the Hyperbolic Crochet Coral Reef is not only an enterprise organized and populated by women, but a feminist one, which tries to credit feminine craft skills as meaningful modes of inquiring into the nature of biological forms and processes. Feminist history of technology was inaugurated by scholars who ably demonstrated not only how technology has been incorporated into the domestic arts, but that women historically have been commanding and savvy technological actors — both as producers and consumers, both within and outside the domestic sphere (Cowan 1983, McGaw 1996). While Marxist theorists have drawn attention to the ways in which scientific management and industrial production have undermined craft labor by decoupling mental from manual labor, feminists have critiqued such claims by demonstrating that skill and know-how are categories with significant social cache that are glossed as masculine (Beechey 1982, West 1990, Weston 1990). Anthropologists of artisanship have foregrounded how craft identities deploy and recapitulate culturally embedded gender norms, whereby self-realization as a craftsperson is often performed according to masculine idioms of hardship and mastery. As a result, craft hierarchies are often legitimated and solidified through the exclusion of women (Herzfeld 2004, Kondo 1990). Other scholars, by examining technologies coded as female, have traced how technology is gendered, and how new technologies can impact gender ideologies (Lerman et al. 1997). Some have argued that traditionally feminine technologies, most notably the fiber arts, must be reappraised to account more carefully for how they have been implicated in the political economies and sociotechnical locales in which they are embedded, and how women have leveraged their expertise in such “gynotechnics” (Barber 1995, Bray 1997).

Whereas the amateur biologists in Chapter 3 work within the masculinist tropes borrowed from both synthetic biology and computer hacking, the women crocheting the Reef are pointedly working in a feminine craft, and, in distinction to synthetic biologists and biohackers, are working *against* the impetus to rationalize, streamline, and standardize biological things. If the technoscientific project, and that of the life and information sciences in particular, has long been recounted in the idiom of masculine birthing (Helmreich 1998), then the Hyperbolic Crochet Coral Reef project, I suggest, is a rejoinder to such tales of biology rendered in bits and bytes: this is a narrative of feminine birthing that draws on regnant, historic, and folk understandings of evolution to claim evolution as akin to feminine craft.

One analogy worth drawing is between the HCCR and Artificial Life, a field that Richard Doyle characterized as “seek[ing] to derive the formal nature of the living system, life’s algorithm, by abstracting it from its material, carbon-based prison” (1991: 121). Reef crafters also abstract life-like qualities from living things, thinking through evolution and morphology as general and abstractable characteristics. Like Artificial Life researchers, in their work I discern echoes of and debts to theoretical and mathematical biologists. Nonetheless, whereas Artificial Life researchers conflated form with formalism, here, I claim, the Wertheims and other contributors recognize simulations of biological forms precisely in their divergence from geometrical algorithms. Early twentieth century theoretical biologist D’Arcy Thompson claimed that morphology arose through mechanical interactions with an organism’s environment,

promoting the use of algebraic and geometric formalisms to account for living form.⁴ Though HCCR contributors use a geometrical algorithm as a starting point for their coralline creations, on their view, the spark of life, or at least life-likeness, resides in swerves *away* from geometrical precision. In this sense, Reef crafters' understanding of biology, and the force of evolution in particular, as open-ended and ad hoc, owes more to François Jacob and Susan Oyama's notion of 'evolutionary and molecular tinkering,' a claim I delve into in more detail later.

After visiting with her at the LACMA workshop, Wertheim invited me over to, as she put it, "see some...IFF things." Besides the Hyperbolic Crochet Coral Reef, the Wertheims have presented exhibits on the Froebelian "gifts"⁵ and a Menger Sponge.⁶ Margaret earned bachelor degrees in both physics and mathematics before embarking on a successful career as a science communicator; Christine received a doctorate in literature and semiotics and now chairs the writing program at the California Institute of the Arts.⁷ Margaret has written about topics

⁴ With the advent of digital computing in theoretical biology in the 1970s, Thompson's work experienced a renaissance among evolutionary and theoretical biologists. For more about Thompson's work and its reception, see Keller 2002.

⁵ German crystallographer Friedrich Froebel, inventor of the kindergarten, developed a series of twenty "occupational gifts," pedagogical explorations of form using paper folding, weaving, and sewing, which were employed in his kindergartens beginning in the 1830s.

⁶ The Menger sponge is a three-dimensional fractal. In the IFF exhibit, electrical engineer and computational origamist Jeannine Mosely built one entirely out of outdated business cards.

⁷ Margaret and Christine were raised in a Catholic family in Brisbane, Australia, two of six children born in the span of five and a half years. They learned many feminine handicrafts from their mother, Barbara, but taught themselves how to crochet in high school and later taught their mother to crochet so that she could contribute to the Reef. Small pictures of Greek and Russian Orthodox and Roman Catholic iconography, as well as a photograph of Margaret meeting then-Pope John Paul II and Cardinal Ratzinger, attest to the Wertheims' background and its continuing influence.

ranging from mathematical origami (Wertheim 2005) to obsolete computational devices (Wertheim 2006). As a science journalist, Margaret has written articles for *The New York Times*, *The Los Angeles Times*, *The Village Voice*, and *Cabinet* magazine; she has published two books on the cultural history of physics and is currently writing a third book profiling an amateur physicist.

What unites all of the IFF's projects is a confluence of physical and mental labor, or what the Wertheims call "figuring," which they recognize in a diverse series of cultural practices, including Indian paisley patterns and Islamic mosaic motifs, "from weaving, knotting and 'string figuring,' to origami, tiling, perspectival drawing, and holography." Summarizing from the OED, Wertheim defines figuring as "to form or shape, to trace, to reckon or calculate, to represent in a diagram or picture, to ornament or adorn with a design or pattern."⁸ In examining the Hyperbolic Crochet Coral Reef, I am interested in understanding how figuring, understood as the confluence of conceptual and manual labor, offers contributors to the Reef access to a craft-based understanding of biological form and evolution, and a way of telling stories — weaving yarns — about how evolution works. As in other constructive biologies, experimentation and manufacture, knowing and making, are here mutually informative.

⁸ Wertheim's understanding of figuring is not unrelated to the way figuring has been theorized by science studies scholars seeking a way to articulate how knowledge is given body. For Haraway, figuration is a move counter to traditional modes of historical representation that is "about resetting the stage for possible pasts and futures. Figuration is the mode of theory when the more 'normal' rhetorics of systematic critical analysis seem only to repeat and sustain our entrapment in the stories of the established disorders" (Haraway 2004). While Harawavian figuration is primarily a rhetorical move, albeit one with real consequences, materialized reconfiguration is a technoscientific project in which her figures engage; it is a way, she argues, "to knot together," and "a practice of turning tropes into worlds" (Haraway 1994: 60). Figuring as a fusion of discourse and materiality also inflects the work of Karen Barad, who riffs on Haraway's materialized reconfiguration to speak of "ongoing material [re] configurings of the world" in a critical epistemological intervention she calls intra-action (Barad 2007). Lucy Suchman emphasizes the *con-* in Haraway's materialized reconfigurations to think through how figures come to be constructed in relation to one another, and to ask how such entities could be figured otherwise (2006).



Figure 4.2. Aviva Alter's First Cambrian Explosion Form.
Photo: Aviva Alter.

Upon entering the Wertheim's home, I found pinned to the wall next to their front door a strange woolly thing in shades of rust and green, a long composite creature with parts variously ruffled, tubular, spiral, and freeform. Its colors and morphology, reminiscent of frilly leaves and bladders, reminded me of some sort of kelp [Figure 4.2]. It is, I later learned, the work of Aviva Alter, a Chicago artist who several years ago attended an Institute For Figuring workshop where

Christine taught her to crochet. This object was the first thing she made, and it ushered in a period in Crochet Reef history Margaret and Christine think of as the “Cambrian Explosion,” because until then the Reef had been entirely composed of what they refer to as “single-celled” species, and Aviva began experimenting with combining different shapes and forms (for example, tubes, spires, and ruffles) in a single crocheted piece to render more elaborate models.

Margaret describes Aviva’s work:

Before the end of the workshop she had set off on her own evolutionary path, which quickly developed into a whole new genera [sic] of crochet reef organisms. These chimeric, hybrid, morphing constructions call to mind the seminal period in the history of life on earth known as the Cambrian Explosion, around 500 million years ago. It was during this era that all the major animal body plans seen on our planet today came into being. So also Aviva's forms seem to suggest the potential of all living things.⁹

What are the conditions that enable Alter and other members of the dispersed assemblage of ecologically-minded craftspeople (overwhelmingly, craftswomen) who crochet coral reefs for display in state fairs, art galleries, and science museums in the United States, Australia, and Europe, to describe the work they do in such explicitly biological terms, to speak of a “Cambrian explosion” and a “Silurian atoll”, to claim that they are fabricating new taxa, genera, and species, to liken yarn to a strand of DNA that encodes biological form?

While Taimina invented hyperbolic crochet as a means of modeling geometric space, reef crafters emphasize that the algorithmic approach to hyperbolic crochet does not yield what they

⁹ http://crochetcoralreef.org/contributors/aviva_alter.php

Alter describes her approach to hyperbolic crochet in her artist’s statement:

I start by posing questions and statements that define human nature and experience, questions that have no certain answer. In crochet I have found a place I can create forms. Making an endless structure comes to me as an organic process using yarn and plastic. This is a place I focus my attention on improvisational form along with thoughts concerning the planet, environmentalism and my own place in this world (Alter 2008).

consider to be “biological” forms. Liveliness, for reef crafters, is best captured by swerving away from such precision. Natasha Myers argues that “liveliness” is a narrative effect of researchers’ embodied work modeling protein conformations, a way of telling stories about biology that “keeps bodies in time” (2008: 246) and “conjure[s] a living world that escapes capture” (250). When crafters realize biological forms in abiotic media, “liveliness” is similarly performative, as it is a playful experiment in the forms “life-like” things might take. That is, the crafters themselves generate the “liveliness” they identify with their woolly simulations of biological forms. In a further transaction, they site liveliness as a general category by which to identify everything life-like. Richard Doyle unpacks the rhetorics by which Artificial Life researchers conflate the “lifelike” with “life itself,” suggesting that the work of turning “models of life” into “examples of life” points to an absence of a coherent reference for life, even as it grounds life in abstractable formal properties (1997: 122). Both Myers and Doyle emphasize that liveliness is rhetorical and narrative — it gets spun from the stories people tell about life.

I am listening for the “evolutionary yarns” Reef crafters spin while trying to make evolution manifest in yarn. *To spin a yarn*, according to the OED, is nautical slang meaning “to tell a story (usually a long one).... Hence *yarn* = a (long story or tale: sometimes implying one of a marvellous or incredible kind.” Evolutionary yarns are indeed long ones, stretching billions of years, and as its etymology suggests, these “evolutionary yarns” are also maritime. Gananath Obeyesekere writes that “one technique in spinning a yarn is to make the fantastic seem matter of fact.... yarnsters incorporate well-known ethnographic truths that then are turned inside out and woven into an episode in a story” (2005: 183). The yarnsters I describe spin their tales from

theoretical biology, ranging from Romantic notions of life forwarded by the likes of Johann Friedrich Goethe and Lorenz Oken, as well as twentieth century theoreticians such as D'Arcy Thompson, François Jacob, and their updates in the work of Susan Oyama and Niles Eldredge.¹⁰ As an ethnographic yarnster, I invert Obeyesekere's formula, to "make the matter of fact seem fantastic."

Whereas in *Artificial Life*, "liveliness" was detectable in digital "creatures" miming or simulating living behavior, while researchers divorced life from bodies, the women crocheting the Reef discover liveliness in the evolvability of morphologies. Though theoretical biologists throughout the twentieth century, among them D'Arcy Thompson, C.H. Waddington, and Brian Goodwin, have sought both to generalize and formalize biological form and transformation using principles borrowed from mathematics and geometry, here is one case in which the spark of life strays from mathematical exactitude. Evolution, crafters claim, is akin to craftwork in its open-endedness. Indeed, the Reef's origin story, which I will retell soon, like all good creation myths, mixes inert matter with a creative gesture to yield something more. To quote Wertheim, "suddenly the models came to *life*."

In this chapter I am interested in thinking through the Hyperbolic Crochet Coral Reef as an instance of constructive biology, which I construe as being about hooking together knowing and making, such that fabrication is, more than materializing metaphors or rearranging

¹⁰ In this sense, the Reef may be thought of as an "experimental system," a material thing that accommodates myriad narratives: "An experimental system has *more stories* to tell than the experimenter at a given moment is trying to tell with it. It not only contains submerged narratives, the story of its repressions and displacements; as long as it remains a research system, it also has not played out its excess. Experimental systems contain remnants of older narratives as well as fragments of narratives that have not yet been told" (Rheinberger 1994: 91, quoted in Doyle 1997: 157n58).

configurations of things, a mode of improvisational and exploratory, materially engaged craftwork, a constructive grappling with biological models apprehended via their manufacture. Constructive biologies like this one indicate a new sort of engagement with biology, one whose characteristics can also be found in professional laboratories and research centers. This approach is about apprehending biology not only materially, but also processually, in and through its making, as, for example, synthetic biologists do. For both synthetic biology and the HCCR, one consequence of such a process-oriented grasp of biology is that practitioners construe biology as itself a process (specifically, an evolutionary one) that, like crafting, tends to be changeable, error-prone, messy, and at risk. However, synthetic biologists aim to rationalize and streamline evolution, while HCCR makers instead simulate evolutionary unpredictability.

In her introduction to *Things That Talk*, Lorraine Daston writes that “like seeds around which an elaborate crystal can suddenly congeal, things in a supersaturated cultural solution can crystallize ways of thinking, feeling, and acting” (2003: 20). I here take the Hyperbolic Crochet Coral Reef as such a seed in cultural solution. It is an artifact — a culturally meaningful material thing — that condenses current ways of thinking and enacting shared biologies (similar to the “shared cellularity” enunciated by sonocytologists). By figuring evolution as a mode of craft, biology becomes something whose evolutionary unfoldings HCCR contributors not only mimic, but also analogically generate, through their ad hoc crafting of new crochet forms. Finally, contributors to the Reef are making a moral argument by reference to the brooding and piecemeal work of reef building as to how craft may productively integrate conceptual and manual work.

THE CONTOURS OF CRAFT: A FIELD DAY AT THE LACMA

Before touring the Wertheims' home and the collection of wooly *objets d'art* that adorn it, I will explain how the Reef gets made, and about the technique of hyperbolic crochet that it applies.

While the Reef has become an “experiment in Darwin’s ideas” (Wertheim, unpublished manuscript) 170 years after coral reefs proved themselves good for Darwin to think with, it started as an exercise in mathematical form. What differentiates mathematical figuring from biological figuring, at least for the Wertheims and their contributors, is that biological figuring is, as they put it, “an experiment,” whereas mathematical figuring, at least for them, is not. By experiment, they mean a practice that is open-ended and dynamic, the product of which is unclear or unanticipated by those undertaking it, akin to Hans-Jörg Rheinberger’s experimental systems, which he characterizes as “dynamic bodies” that behave as “generators of surprises” (1997: 2-3). While the mathematical figuring that preceded the Reef is certainly a mode of tangible and embodied apprehension of geometric structures, the objects being fabricated are generated algorithmically, and are not meant to generate new forms, but to manifest the hyperbolic plane.

Much of the Reef was fabricated by the Wertheim sisters, with the help of around fifty prolific contributors, but many of the pieces are one-off objects that either arrive by post in boxes at the Wertheims' front door or are made in workshops or craft circles in New York, Chicago, London, Scottsdale, Sydney, Riga, Toronto, and Tokyo. My first visit to the Wertheims' home was a week and a half after I attended one such workshop at the Los Angeles County Museum of



Figure 4.3. “Christine Wertheim of the Institute for Figuring, center left, leads a workshop on crocheting plastic trash bags into coral-like forms.” The author is seated on the right.

Photo: Kevin Scanlon, *The New York Times*, November 28, 2008.

Art. The workshop they hosted was part of a larger event run by Machine Project, a non-profit organization in Echo Park, California that, according to its mission statement, “exists to encourage heroic experiments of the gracefully over-ambitious.”¹¹ At LACMA, about 25 different groups hosted workshops for 10 hours on a warm Saturday. The IFF workshop was

¹¹ This aim pans out in regular classes that teach curious amateurs how to program in Arduino (a physical computing platform designed for use by hobbyists and technoartists), use a sewing machine, build a synthesizer, or pickle vegetables.

stationed in a large gallery on the second floor of the Ahmanson building, where Margaret and Christine arranged two tables into an L flanked by a few Pollocks and a Rothko [Figure 4.3].¹²

The sisters had covered the tables in butcher paper and arranged a number of crocheted pieces on each table, as well as craft materials: crochet hooks, scissors, and plastic bags. Their workshop focused on how to crochet plastic models, in reference to the threat plastic trash poses to the health of the world's oceans. To make a plastic trash hyperbolic crocheted coral, one must first make plastic yarn, and this is what Christine set out to teach me once I sat down. Sitting beside me in the LACMA gallery, Christine first took two plastic bags, white with red lettering, and folded them lengthwise into quarters. After using scissors to trim the handles and bottom, she began cutting strips of plastic crosswise which, once unfolded, made plastic loops about half an inch wide. Folding and cutting my own plastic bag, I followed Christine's lead. After we had both accumulated a handful of plastic loops, Christine showed me how to pass one loop over and then under a second one and pull it through, in the way one would make a chain of rubber bands. Once I had a good length of plastic yarn ready, I made a slipknot and began crocheting a chain, then worked my way back around the first thirty stitches, increasing every fourth stitch.

Christine set out several years ago to begin crocheting a single hyperbolic model which she

¹²Rothko, champion of color field painting, described his work in a way I find sympathetic to fellow Latvian and hyperbolic crochet inventor Daina Taimina: as "unknown adventures in an unknown space" lacking "direct association with any particular, and the passion of organism" (1947). But sitting between Jackson Pollock's "Black and White Number 20" (1951) and Rothko's "White Center" (1957), I found ironic the disjuncture between the IFF workshop's aims — to teach the technique of hyperbolic crochet and to encourage mass participation in fabricating the Reef — and the Modernist, and in particular Abstract Expressionist, setting. Many craftspeople and scholars of craft eye Modernism, with its attribution of individual artists and "distrust of skill and fine craftsmanship," with suspicion. Jeweler and author Bruce Metcalf comments, "The history of modern art records a gradual abandonment of the traditional crafts.... By the late 1940s, Jackson Pollock could pour house paint on a canvas, throw his cigarette butts onto it, and be heralded as the hero of American painting. The uncrafted gesture now stands for authenticity and raw emotion" (Metcalf 2007: 14). It was here, in a gallery ostensibly applauding the "uncrafted gesture," that the Wertheim twins set up shop to teach curious passersby how a craft technique may be pressed into service when embarking on "unknown adventures" in hyperbolic space or in celebrating "the passion of organism."

would continue to work on throughout her life, using crochet as a benchmark and a trace of the passage of time. She imagined that whereas the first few rows or rounds would take minutes to complete, because hyperbolic geometry is an “excess of surface,” the final row or round would require decades.¹³ Her mapping of biographical time onto the efflorescence of hyperbolic geometry is an experiment in figuring, within which the time-intensive work of craft, the slow accretive process of evolution, and the discursive work of autobiography all hang together.

Wertheim first learned about hyperbolic crochet from an article in the *New Scientist* about the “power of traditional handicrafts” like crochet, knitting, and glassblowing “to create otherwise unimaginable [mathematical] objects” (Brooks 2001). The article mentioned mathematician Daina Taimina, now an adjunct associate professor in the Department of Mathematics at Cornell University, who fabricated the first robust physical model of hyperbolic space.¹⁴ Taimina first came to Cornell as a visiting scholar in 1997, tasked with teaching David

¹³ Christine plans to abandon work on this project soon, as she has already generated so much surface area that the edge of her crocheted form has curled in upon itself, making it difficult to add to it. It is also becoming increasingly hard to carry around.

¹⁴ Previous models had been purely conceptual, such as the Poincaré disc model, but in the mid-twentieth century, geometers identifying with the intuitionist school of mathematics “wanted to have a more direct experience of hyperbolic geometry — an experience similar to handling a physical sphere” (Taimina, quoted in Wertheim 2004) and began casting about for a physical model.

Henderson's hyperbolic geometry course.¹⁵ Henderson had constructed a physical model of hyperbolic space while on a camping trip in 1978, and used it in his course for the next nineteen years. He had fabricated the model using small paper annuli, or rings, which he then taped together, following a method he had learned from fellow Cornell geometer William Thurston.¹⁶ Taimina described the twenty-year old paper model as "disgusting" and too flimsy and friable to easily handle or play with. That sturdiness was one condition of a good model speaks to Taimina's pedagogical bent: she wanted a model that students would not just look at, but *handle*,

¹⁵ Hyperbolic geometry was explored in the 1820s by Janos Bolyai, a hungarian cavalry officer who spent his free time dueling, playing the violin, and trying to prove Euclid's fifth postulate (Gardner 2001: 177). Also known as the parallel postulate, Euclid V states that given a line and a point outside that line, there exists only one line intersecting that point parallel to the first line. Many mathematicians believed that Euclid's V could be derived from his first four postulates, but by the end of the eighteenth century, no one had yet successfully done so and the postulate had become a 2000-year itch mathematicians could not scratch. Bolyai focused his attention on the parallel postulate after his father, Farkas, had tried unsuccessfully to tackle it (Lines 1994: 41). So maddening did Farkas find the parallel postulate that he wrote to Janos, "For God's sake, I beseech you, give it up. Fear it no less than sensual passions because it too may take all your time and deprive you of your health, peace of mind and happiness in life" (Gardner 2001: 176). Other sources quote Farkas, a man clearly prone to hyperbole and nay-saying, petitioning his son: "I admit that I expect little from the deviation of your lines. It seems to me that I have been in these regions; that I have traveled past all reefs of this infernal Dead Sea and have always come back with broken mast and torn sail" (Meschkowski 1964, quoted in Greenberg 1993: 162). Persisting in this work, Janos discovered that a self-consistent geometry could be envisioned by rejecting the parallel postulate. He wrote to his father in 1823: "I have not quite reached it, but I have discovered such wonderful things that I was amazed.... *Out of nothing I have created a strange new universe*" (Greenberg 1993: 163). Bolyai shares recognition for the discovery of hyperbolic space with Russian mathematician Nicholay Lobatchevsky, who worked on the problem at the same time as Bolyai but published earlier. This is the mathematical foundation of hyperbolic geometry: it is a space in which for any line and a point outside the line, there exists an infinite number of lines intersecting that point that are parallel to the first line (elliptical geometry [like the surface of a sphere] is also non-Euclidean, but instead of an infinite number of parallel lines, on a sphere there exists no line parallel to a straight line that intersects a point outside that line). While Euclidean geometry is planar (no curvature) and elliptic geometry is spherical (positive curvature), hyperbolic geometry displays negative curvature, meaning that at every point, the surface curves away from itself exponentially (compare to a sphere, the surface of which closes in upon itself). Wertheim gets a lot of mileage from contrasting the seeming formality of Greek mathematics with the eminently approachable crochet hyperbolic models. In a 2009 TED (Technology Entertainment Design) conference lecture, she held up a floppy red hyperbolic model, announcing to the audience that "here in wool, through a domestic feminine art, is the proof that the most famous postulate in mathematics is wrong" (Wertheim 2009).

¹⁶ Thurston was not the first to devise a model of hyperbolic space made out of paper: "In 1868, the Italian mathematician Eugenio Beltrami had described a surface called a pseudosphere, which is the hyperbolic equivalent of a cone. Beltrami made a version of his model by taping together long skinny triangles — the same principle behind the flared gored skirts some folk dancers wear" (Taimina, quoted in Wertheim 2004).

and so set out to fabricate new hyperbolic models from yarn.¹⁷ Daina Taimina learned needlework from her mother as a girl in Soviet Latvia. She describes the resourceful ethos that marked Soviet culture during her childhood: “You fix your own car, you fix your own faucet — anything.... When I was growing up, knitting or any other handiwork meant you could make a dress or a sweater different from everybody else’s” (Samuels 2006). Unlike Wertheim, Taimina does not differentiate between the formalisms of geometry and the more grounded and mundane aspects of daily life — she points to the mushrooms and parsley in her garden as examples of hyperbolic geometry, and uses the technique she developed to model the hyperbolic plane also to fashion clothing.¹⁸ Beyond representing or intervening, hyperbolic crochet as a figuring practice points us toward a wooly tangle in which handiwork grounds mathematical apprehensions and vegetable gardens embody geometric structures.

Though Taimina’s models got their start as pedagogical tools, she also emphasizes the material tactility of her fabrications as being necessary for the comprehension of geometrical spaces that would otherwise remain purely conceptual and, to a large extent, unfathomable.

While certainly handling a physical hyperbolic model allows one to apprehend the geometry of hyperbolic space better than equations or a two-dimensional diagram of hyperbolic geometry

¹⁷ “So I spent the summer crocheting a classroom set of hyperbolic forms. We were sitting at the swimming pool with David [Henderson]’s family, my girls were learning to speak English and swimming, and I was sitting and crocheting. People walked by, and they asked me, ‘What are you doing?’ And I answered, ‘Oh, I’m crocheting the hyperbolic plane’” (Samuels 2006). Taimina quickly switched to crochet after finding that knitting was not the ideal technique for fabricating hyperbolic models: to knit a hyperbolic model requires that you increase every N stitches, and when knitting, all the stitches in a row must remain on the needles. Depending on your rate of increase, you very quickly run out of room on the needles as there are too many live stitches in play. In crochet, on the other hand, only the current stitch is kept on the hook, so the number of stitches can increase exponentially without crowding the crochet hook. Also, crochet yields sturdier and less floppy forms than does knitting.

¹⁸ In an interview with *Discover* magazine, Taimina points out that hyperbolic crochet is good for more than geometry — she also uses the technique to make her own clothing. She crocheted a hyperbolic godet skirt to wear at a talk at the IFF, “after which the film director Werner Herzog took her to dinner and then kissed her good night. The skirt is made of 10 skeins of cotton yarn, each of which is 689 feet long” (ibid).

would, it only goes so far. What is most diagnostic of the intersection of handicraft and geometrical models is practitioners' insistence that to understand these puzzling geometries, you not only need to interact with a physical model, but that you need to take the time to *make one yourself*.¹⁹ Wertheim told Daina Taimina in conversation that:

I have crocheted a number of these models and what I find so interesting is that when you make them you get a very concrete sense of the space expanding exponentially. The first rows take no time but the later rows can take literally hours, they have so many stitches. You get a visceral sense of what "hyperbolic" really means (Wertheim 2004).

The "visceral sense" of which Wertheim speaks is about a deep material apprehension of a thing that is best imparted by making it, and more so, by making it slowly. It is the time and physical work put into crocheting, and the improvisational experimental work of generating new forms, that offers crafters embodied understandings of biological form and evolution. This close understanding that comes from fabrication is not unique in scientific practice. In her biography of Nobel Prize-winning geneticist Barbara McClintock, Evelyn Fox Keller asserts that it was McClintock's "feeling for the organism" that afforded her the ability to notice and interpret anomalies in her model organism. While she never defines this "feeling," she suggests that it is about an intimacy, identification, and discernment of the thing being studied, which McClintock refined by cultivating her maize plants herself, sitting in the field and being willing to slow down

¹⁹ This is the claim made by University of Bristol geometers Hinke Osinga and Bernd Krauskopf, who in 2004 published instructions in the *Mathematical Intelligencer* for crocheting the Lorenz manifold, a geometrical surface related to the Lorenz attractor, a well-known model of non-linear deterministic dynamic systems, which has practical applications in predicting weather patterns (think of the Butterfly Effect). In their publication, Osinga and Krauskopf write that the three-dimensional crocheted model of the manifold is able "to convey the intricate structure of this surface in a 'hands-on' fashion. This article tried to convey this, but for the real experience you will have to get out your own yarn and crochet hook!" (ibid). Osinga, whose mother taught her to crochet when she was seven, explained in an interview with *Craft* magazine that while she had previously developed computational models of the Lorenz manifold, "the crochet project was 'driven by the need to see and feel the real thing'" (ibid).

and “take the time” with her organism (1983). “Taking the time” and the “visceral sense” that it engenders are necessary to and afforded by acts of mathematical and biological figuring in which understanding things like hyperbolic geometry and evolution is worked out through fabrication.²⁰

When I was seven years old, my grandmother taught me to crochet to alleviate my boredom and distract me from my carsickness on a long, hot, and lurching bus ride (my mother also knows how to knit and crochet, but could not teach me, as she is right-handed, and I, like my grandmother, am left-handed). By the time I read Wertheim’s interview in *Cabinet* in spring 2008, I had not picked up a crochet hook in a good ten years, and my technique was rusty. In order to experience this “visceral sense” firsthand, I decided to try my hand at hyperbolic crochet. I bought three skeins of hot pink cotton yarn and a crochet hook at my neighborhood craft shop.²¹ At home, I took out Taimina’s crochet instructions, which had been published in an issue of the craft magazine *Interweave Knits* (Lock 2005) and made a slipknot. I had expected to struggle at first, but was surprised to discover that my hands still remembered how to crochet, even if I did not. I knew how to grip the hook and maintain the tension in the yarn, in which direction to grab the yarn with the hook, and where to insert the hook in the previous loop. The first chain of twenty stitches took a few minutes to complete, as I had not yet regained the ease and momentum that comes with continued practice. The second and third rows, even when increasing every fifth stitch, took less time, but each row after that became considerably more

²⁰For other accounts of scientists gaining a “visceral sense” of their objects of study, see Downey 1998, Myers 2008, Traweek 1988. For a review of sociological and anthropological accounts of scientific practice, see Chapter 1.

²¹While Taimina recommends using cheap acrylic yarn to give models more structural integrity, the craft store I went to frowned on acrylics in favor of all sorts of organic sustainable textiles spun from soybeans and alpacas, so I settled for a fairly elastic Greek cotton. I picked hot pink because it seemed like the sort of shade one would find in a coral reef.

time consuming. I worked on my model for a few hours most evenings over the course of two months; crochet is a repetitive gesture easily done while distracted, and sometimes I would look down at what my hands were doing and marvel at the thing taking shape. Artist and scholar Lou Cabeen, in writing about early twentieth century embroidery, describes this satisfaction as “the sensuous pleasure of the work itself,” which she articulates in a biological idiom of bringing forms to life: “cloth in hand, colored threads at the ready, the calming effect of repetitive motion, and the gratification of watching a form grow as if by magic under your fingers, the sense that you were, in fact, bringing it to life” (216). Its negative curvature made it warp and contort in my hands, but, depending on how I adjusted its ruffles, it could take any number of conformations (what mathematicians call “embeddings in 3-space”): a tightly frilled sphere, a spiral chain, a fluted shallow bowl. Whereas I finished the first rows in minutes, I quickly gained the “visceral sense” of what it means for surface area to increase exponentially: the last row took over a week to complete, and a third of the total yarn.

By the time I participated in the Wertheims’ workshop at LACMA, I was again a fairly adept crocheter, and over the course of the afternoon made a halfway-decent hyperbolic coral out of reused shopping bags and a length of gift ribbon, while talking to other workshop participants and passersby. Seated across from me for much of the day was Clare, a middle-school librarian and sometime ceramicist who makes her forms out of the royal blue plastic bags in which her *New York Times* is delivered, interwoven with plastic medical waste such as hypodermic needle covers and bits of tubing from IV lines. I turn in the next section to the Reef itself, and to the

work of Reef contributors like Clare, asking what sort of evolutionary yarns they narrate and generate by crocheting coralline forms.

**“AN EVOLVING WOOLY TAXONOMY:”
A DIVE INTO THE HYPERBOLIC CROCHET CORAL REEF**

Having sketched out the unlikely series of biographical, epistemological, and discursive swerves that entangle crochet, non-Euclidean geometry, marine biology and ecological activism, I now track back to the kitchen in Seahorse Valley. The Wertheims’ home reminded me of a sort of contemporary curiosity cabinet, and when Margaret abruptly stood up from the kitchen table, saying “come with me. I’ll show you some things,” I learned that what she had in mind was a sort of architectural mnemonic, in which she introduced me to the Hyperbolic Crochet Coral Reef and the Institute For Figuring through an extended tour of its artifacts, which were artfully arranged on every horizontal surface of her home.

Taking out a ziplock bag, Wertheim arranged before me a series of orange pseudospheres, each about an inch or two in diameter. The work of a graduate student in the natural sciences, these forms exhibited the sort of mathematical precision with which the project started. Each pseudosphere was labeled with its rate of increase, varying from every six stitches, which produces a softly fluted form, to every two, yielding a tightly curled mat.

After Margaret read the article in *New Scientist*, she decided to try Daina Taimina’s technique because she had not crocheted in a long time and thought it would be fun. The article, however, was unclear about what Taimina’s technique had been, so Wertheim called Taimina to

ask for further instructions. She and Christine started crocheting, making many mathematically accurate forms in the first few months. Margaret was very particular about being true to the “pure geometry” of the forms, wanting to see how far afield they could go by following the rules of hyperbolic crochet (that is, increasing after a prescribed number of stitches, and not varying the rate of increase), but Christine started complaining that she was bored. Having crocheted piles of geometrically accurate hyperbolic planes, Christine one day said “screw geometric fidelity,” and started diverging from the algorithm,

deviating into irregular rates of increasing stitches and un-planar forms. To this algorithmic aberancy [sic] she soon added fluffy and hairy yarns; she also started mixing yarns together — a bright orange synthetic with a hot pink mohair, for instance, or a deep green carpet yarn with a hairy cream boucle. The effect was electrifying. Suddenly the models came to *life* — they began to look like natural organisms instead of Platonic ideals.²²

Recounting that period, Margaret says that as soon as they started diverging from what she calls the “pure geometry,” the forms began to look biological:

But we found that when we deviated from the specific setness of the mathematical code that underlies this, the simple algorithm crochet 3, increase 1, when we deviated from that and made embellishments to the code, the models immediately started to look more natural (Wertheim 2009).

What do the Wertheims mean when they say that they brought the models “to life?” The “code” Margaret speaks of has multiple referents: it is the mathematical formula encoding the hyperbolic plane, the crochet pattern that materializes hyperbolic space, and the genetic code,

²² http://www.theiff.org/reef/contributors/christine_wertheim.html, emphasis in the original.



Figure 4.4. Evelyn Hardin's "White Spire Tube-Worm" grove.
Photo: Francine McDougall.

"mutations" in which Wertheim and her contributors imagine engendering the production of new forms. Thinking about the code as "genetic" does not necessarily suggest an alliance with DNA; until the early twentieth century "genetic" also had the broader sense of anything "generative; productive," marking spaces of productive possibility including but not limited to biotic substrates (OED). Just as genetic mutations can drive evolution by giving rise to new biological forms, the crocheters' prerogative to stray from a formal series of rules is what drives, in the Reef, the proliferation of new forms, which Wertheim and Reef contributors describe as

“species.” Not all contemporary biologists narrate evolution as strictly molecular, nor as genetic. Such an account revives gene-centric stories about genes as agents of individual evolvability, which had their heyday in classical molecular genetics and remain central to folk understandings of mutation and evolution. They do so at the expense of more recent theoretical biology theories that complicate and tangle Darwinian and neo-Darwinian explanations by accounting for phenotypic, population-wide, and epigenetic change as also vital to evolution — for example, studies of macromutation, natural selection, environmental adaptation, epigenesis, and lateral gene transfer.

In 2005, Margaret and Christine took a handful of the freeform hyperbolically-derived forms they had crocheted and arranged them on their coffee table. Having grown up in Queensland, home to the Great Barrier Reef, the twins were attuned to the threat climate change posed to coral reefs, a problem that had been gaining attention in the popular press over the past decade. The arrangement of hyperbolic forms on their coffee table suggested a reef, and Christine thought they should continue crocheting until they had fabricated an entire crocheted reef that they could exhibit. Margaret soon realized that the work required to crochet a coral reef was much more than the twins could handle alone, so she posted a call on the Institute’s website, encouraging others to contribute their time crocheting the Reef.²³

²³ The first exhibit was not, however, strictly coralline. Instead, the forms were displayed as a cactus garden and kelp forest in the gems and minerals cases in the tapestry hall, as part of the Fair Exchange exhibit of the 2006 Los Angeles County Fair, which Wertheim describes as “the world’s biggest celebration of prize-winning animals and home-baked wonders.” The cactus and kelp were exhibited, Wertheim recounts, between the quilts and the Christmas ornaments. Around the same time, one of the first responses she received to her online call was from the Andy Warhol museum in Pittsburgh, which was organizing an exhibit on global warming. Wertheim remembers, “I laughed and said, ‘Well, we’ve only just started it. You can have a little bit of it’ (2009).

Standing up from the kitchen table, Margaret pointed out the work of Evelyn Hardin: a delicate purple creature with ruffled tentacles layered radially like the petals of a flower, perched in a wine glass on the kitchen sideboard so that its tentacles draped artfully over the glass stem. Evelyn, a middle-aged woman from Cedar Springs, Texas, regularly ships boxfuls of her creations to Seahorse Valley [Figure 4.4]. Sometimes Margaret and Christine mail her offerings back, asking her to alter or tweak them in some way, and Evelyn complies.

Hardin, whom I later interviewed in Cedar Hill, Texas, often crochets until three or four in the morning. In her current work, she is crocheting models whose rate of increase follows the Fibonacci sequence, which she said she thinks of as a “rate of growth” in organisms.²⁴ Margaret told me a story about Evelyn that reminds me of a line from a short story by feminist science fiction author Ursula K. Le Guin. “Sur” is a fictional account of an envoy of South American women explorers sent to the South Pole in 1909-1910. In the story, the home kept by the women explorers is contrasted to the slovenly camp kept by British male explorers. The narrator remarks, “housekeeping, the art of the infinite, is no game for amateurs” (1982: 41). The statement is subversive, as it suggests that there is a professionalism and virtuosity to housekeeping often left unrecognized, while also recognizing that it is a perpetual task. The hyperbolic crochet coral reef is, however, marked as a “game for amateurs”: Wertheim avoids referring to her contributors as professionals, much to their chagrin. In a press release for an exhibit at Track 16 Gallery in Santa Monica, Margaret described Evelyn as a “madly creative Dallas housewife.” Evelyn emailed her back, saying that she would prefer to be described as a

²⁴ D’Arcy Thompson first pointed out that many plants bear leaves arranged in the Fibonacci sequence; identifying examples of Fibonacci sequences in nature has since become an almost numinous quest in both professional and popular accounts of evolutionary biology (Green 1987, 1999; Kauffman 1995).

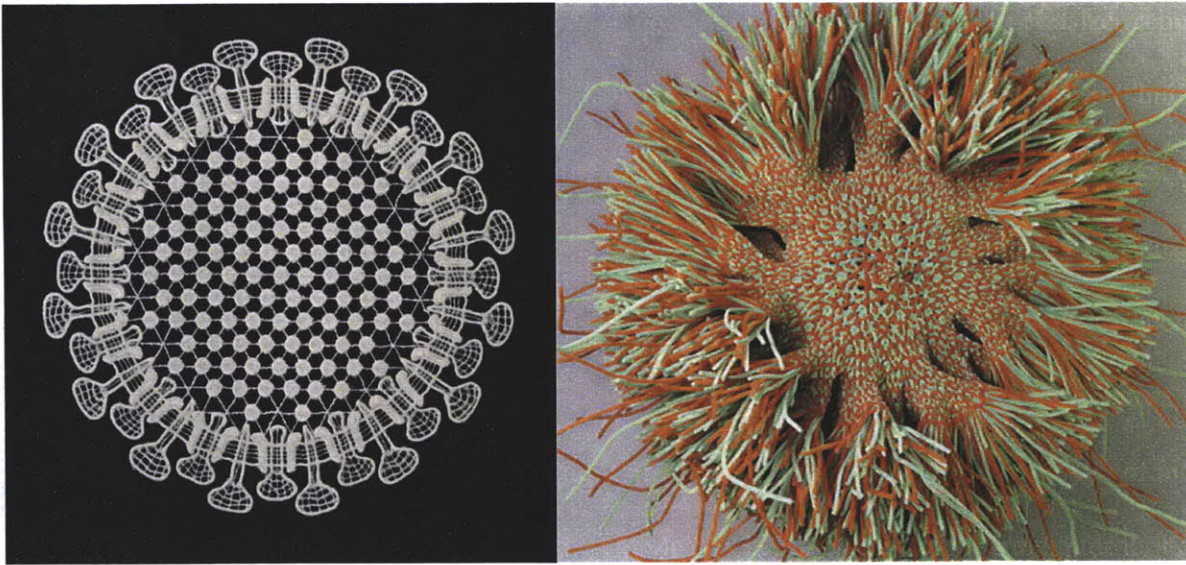


Figure 4.5. Laura Splan’s SARS Doily.

Figure 4.6. Trevor and Ryan Oakes’s Pipecleaners Pseudosphere.

“fiber artist.” Margaret is fond of the adjective “mad” and considers it a compliment — indeed, she tells me that she herself aspires to be a mad housewife. What seems to frustrate her is that there is no credit attached to being a mad housewife, to being uncredentialed or amateur. In part, this tension over whether contributors are “artists” or “amateurs” speaks to the status of “women’s work” in general, which social scientists have shown is often defined by its dismissal as menial, minor, secondary, or not economically productive. In contrast, think of biohackers, who revel in their amateur status (Cowan 1979, Light 1999, Lipartito 1994, Wajcman 2000).²⁵

Moving from the kitchen into the living room, Margaret took down from the wall a piece of lace mounted on black velvet, made by artist Laura Splan, who enters digital images of viruses

²⁵ Yet Margaret does imagine that many of her contributors are mad, in their way, and envisions her role as offering a respectability to their madness: they have what crafters call “their stash” of materials with which to work, yarn and hooks and whatnot, stowed away in craft rooms. She imagines that when these women’s husbands and children chide them for hiding in their craft rooms, working at their “mad projects,” they can now respond, “yes darling, but my work was exhibited at the Hayward [Gallery in London].”

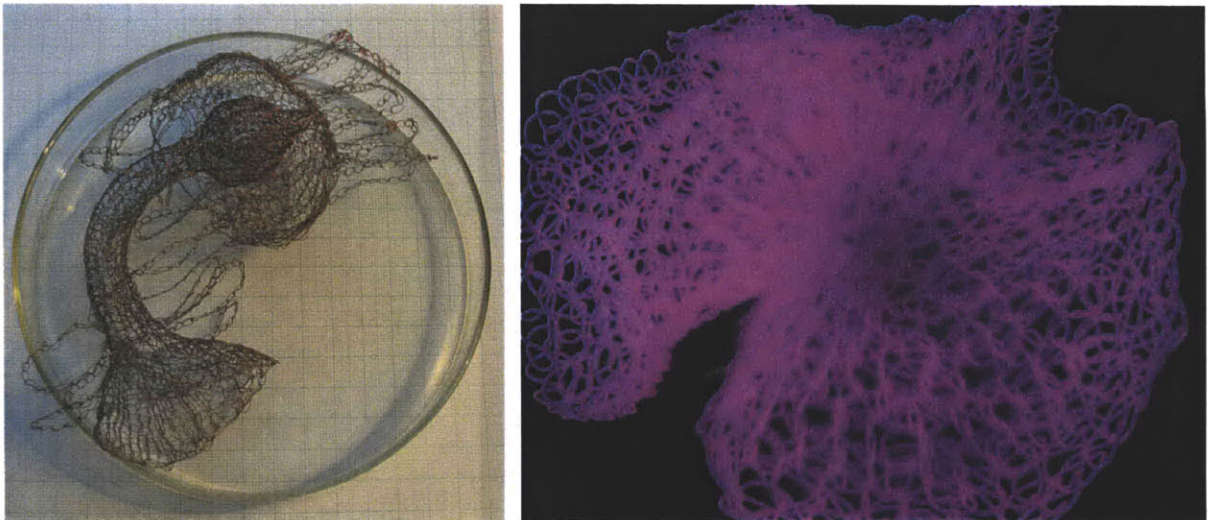


Figure 4.7. Anita Bruce's "Specimen 18 — Fossilised."

Figure 4.8. Eleanor Kent's Electroluminescent "GrannyTech."

like HIV, Herpes, and Influenza into a graphics editor, and then successively into computerized embroidery software and a computerized sewing machine. This particular doily was in the shape of the SARS coronavirus [Figure 4.5]. On the floor beneath the viral doily was a huge pseudosphere of purple and orange pipe cleaners displayed on an overturned cardboard box, the work of twin artists Trevor and Ryan Oakes [Figure 4.6].²⁶ Going upstairs, we walked into a room filled completely with shipping boxes. This was the Reef, packed away. Margaret picked up one box, bringing it back downstairs into the kitchen, where she turned out the lights. Inside the box was an object sent to the IFF by Eleanor Kent, an elderly woman and self-described "visionary artist" who refers to her current work as "granny tech": a hyperbolic form crocheted from electroluminescent wire which, when plugged into the wall, illuminated and flickered like a strobe light, or some bioluminescent deep sea creature [Figure 4.7].

²⁶ Many of the pieces Wertheim showed me were either not strictly hyperbolic in form, not manufactured using crochet, or not meant to evoke coral, although the vast majority of the pieces in the Reef meet all three criteria. Some work (Splan's) meets none of them, but is included nonetheless because it cites biological form using some medium of traditionally feminine handicraft.

Walking back into the living room, Margaret pointed out the work of Anita Bruce, a British computer programmer who returned to school as an adult to pursue a B.A. in fine arts [Figure 4.8]. The Wertheims describe their introduction to Bruce's sea creatures, which she carried to the Hayward Gallery in a Tupperware container, on their online reef gallery:

Here was an entire invented taxonomy of magical sea creatures, all knitted out of fine scientific wire. Over several years Anita had been pursuing her own evolutionary path, beginning with very simple forms then letting the process of stitching guide the development of the "organisms" into increasingly complex structures. Like us, she too was proceeding along a private Darwinian path, allowing the inner nature of her work to develop and grow organically.²⁷

An evolutionary algorithm Bruce developed dictates the morphology of the forms — how many bulbs, tentacles, or cones grow from their trunks, and in what configuration — which she then knits on tiny needles from scientific wire. The result is delicate transparent lacy sea creatures that Bruce submits to a process of artificial selection, making more of those forms that she likes, and retiring those she does not. In her artist's statement, Bruce explicitly draws a parallel between craft practice and biological evolution:

Specimens are constructed in thread using simple elemental looping techniques, which are amongst the earliest used by man to construct fabric and practical objects such as nets and baskets. They reflect my interests not only in the evolution of life, but also in the archaeology and evolution of stitch. Simple stitches are the building blocks that create complex forms. The repetitions of stitch construct a fabric from thread that also references the generations it takes to create each new "species." This cell-like network represents the life cycle and complex connections that balance the natural world. The linear thread of the textile thereby draws on and mimics the continuity of life itself, as organised by the pattern of DNA (Bruce unpublished manuscript).

²⁷ http://crochetcoralreef.org/contributors/anita_bruce.php

While Bruce emphasizes regularity and the bottom-up manufacture of complex forms by repeating basic stitches (“building blocks”), a reading of her work that resonates with synthetic biologists’ use of BioBricks, the work of Aviva Alter (the artist whose freeform invocation of the Cambrian Explosion had caught my eye earlier) is more spontaneous and exploratory. The craft of crocheting hyperbolic geometries has become an analog for biological evolution, such that the Wertheims, reef contributors, and journalistic treatments of the reef increasingly narrate evolution itself as a sort of biological craft practice, and craft in turn as a mode of woolly evolution. Wertheim describes Taimina’s models as being “the generative seed for the Crochet Reef project,” within which “crochet ‘organisms’ mutate and evolve” (Wertheim, unpublished manuscript). The notion of evolution as craft owes a rhetorical debt to François Jacob, the molecular biologist best known for his work with Jacques Monod on transcriptional regulation. In a series of lectures delivered in the late 1970s and early 1980s, Jacob put forward his theory of “evolutionary tinkering,” claiming that though natural selection is compared to engineering design, homology and exaptation suggest instead that natural selection “resembles not engineering but tinkering, *bricolage*” (1982: 34).²⁸ Quoting Levi-Strauss, Jacob described the tinkerer as someone who

manages with odds and ends... old cardboard, pieces of string, fragments of wood or metal, to make some kind of workable object. As pointed out by Claude Lévi-Strauss, none of the materials at the tinkerer’s disposal has a precise and definite function. Each can be used in different ways.... This process is not very different from what evolution performs when it turns a leg into a wing, or a part of a jaw into a piece of ear (ibid: 34-5).

²⁸One version of this lecture was published as a *Nature* article; it has been cited 949 times, mostly by biologists and other stripes of evolutionary theorist, among them popular figures such as Steven Pinker, Stephen Jay Gould, and Francis Crick.

Evolutionary tinkering, Jacob continued, is most apparent at the molecular level: “it is difficult to see how molecular evolution could have proceeded if not by turning old into new by knotting pieces of DNA together — that is, by tinkering” (ibid: 39). Susan Oyama used Jacob’s claim to rethink ontogeny, claiming that

both processes [of evolution and ontogeny] show the contingent quality of tinkering, in the sense not of randomness or disorder but rather of subtle and opportunistic dependence on particular conditions and materials.... Rather than the directedness of planned activity, it is such inspired tinkering that characterizes life processes, the marvelous results notwithstanding. In the case of normal development, however, the scraps and bits of twine are all at hand (1985: 46).

Jacob’s evolutionary tinkerer offers a compelling riposte to the teleological stories about evolution that snuck into theoretical biology with cybernetics and information theory, and to which Artificial Life researchers and synthetic biologists, in fantasizing about “optimizing” biological design, have also been committed.

This description of the project’s mutation and evolution also suggests a somewhat Romantic conception of biology, especially given that Margaret also thinks of Taimina’s work as a series of “Platonic forms” from which a diversity of living forms have spawned. The notion of “Platonic forms” calls to mind Romantic biologists’ preoccupation with what Goethe termed *Urformen*, archetypes that change and transfigure as they branch out across the plant and animal kingdoms. Margaret also affixes epigraphs by German *Naturphilosoph* Lorenz Oken to the walls of Reef exhibits.²⁹ Oken, like Goethe, was interested in the ideal forms from which all living things

²⁹“Everything has been created out of sea-mucous, for love arises from the foam” (Oken 1826).

ramify, and posited that bodies also contained potential living forms, as yet unrealized. The Wertheims recognize Ernst Haeckel as a “patron saint” who “hovers over the crochet reef as a guiding spirit.” They cite his “hyperbolically detailed” scientific illustrations of marine life-forms as inspiration, but Haeckel’s view of a “fecund nature from whose creative depths greatly disparate forms could arise” also evokes the Reef’s ambitions (Richards 2008: 9). Indeed, the Romantic emphasis on appraising living form using one’s cultivated aesthetic judgment also underwrites the Reef project. Robert Richards describes Haeckel’s approach to evolutionary theory as the marriage of aesthetic ideal types to concrete forms, and Richards describes Haeckel’s archetypal biological form as “a polymorphous organism — a perverse sponge artfully conceived,” to which other organisms would display homologies early in their development (ibid). Haeckel’s “perverse sponge” is echoed in the fibrous realizations of baroque marine forms.

Margaret claims that “one of the most surprising aspects of the Crochet Reef project has been the way in which evolution takes place within this woolly world,” and that “over time we have witnessed the emergence of a fantastical taxonomy of crochet reef ‘species’” (unpublished manuscript). The project, in her terms, “serves as a kind of spontaneous global experiment in Darwin’s ideas” (ibid). What seems to be vivified in rhetorical moves such as these is the reciprocal and improvisational attention to material that marks much handiwork, as well as the creative flourishes or personal idiosyncrasies that determine and get built into new crochet coral kinds. Nouns like “organisms” and “species” are quarantined in scare quotes while verbs like “mutate” and “evolve” are left to commingle in these analogies because Reef crafters cast

biology as process rather than substance, a process that may transpire in yarn as in other, more properly biotic, media. One way to put this distinction would be to say that the Hyperbolic Crochet Coral Reef, for those who make it, is not alive, but it does seem to be living (and mutating and evolving and spawning). Whereas Artificial Life researchers who posit that evolution is a universal category not limited to biological things collapsed life onto information, Reef crafters draw on commonsensical understandings of evolution to keep both form and matter in play in their models. Evolution might take place in abiotic media, but it remains very much material.

The belief that crafted or manufactured artifacts can also evolve is not limited to Reef crafters. Philosopher of biology Gilbert Simondon arranged telephones and motors in series reminiscent of embryological atlases to demonstrate their “morphological evolution” (Simondon 1958; for a historical account, see Schmidgen 2004). Niles Eldredge, the paleontologist who, together with Stephen Jay Gould, advanced punctuated equilibrium in 1972, is a dedicated horn player who now analyzes the diversity of cornet (a soprano brass-wind instrument) morphological vectors (as he earlier studied trilobite morphology) in order to track what he calls “material cultural evolution” (Eldredge 2000). Though many, including anthropologists (social evolutionists and cultural ecologists, in particular), have analogized culture to evolution, Eldredge tweaks this folk sensibility by suggesting instead that culture works more like lateral gene transfer. This perspective no doubt impacted Margaret’s thinking about the Reef after she interviewed him for a *New York Times* article in 2004. She summarizes his understanding of lateral transmission of crafted objects: “culturally produced objects are also subject to what is

called lateral transmission. Once a manufacturer comes up with an innovation — say a new style of cornet valve — it can easily be copied by others, spreading the new pattern across the population pool” (2004). The evolutionary yarn woven here is a knotty one, in which craft configures kinship and descent dissolves in cultural solvents.

The open-ended creative work performed by reef crafters is narrated in an evolutionary idiom: the Wertheims characterize the Reef as “a vast, ongoing, evolutionary experiment” in which each crafter’s open-ended exploratory iteration of hyperbolic crochet is analogous to an evolutionary impetus. It is a commonplace of evolutionary theory that evolution proceeds through environmental pressures acting upon random mutations, which has the effect of promoting the survival and reproduction of those organisms whose mutations are adaptive. Error in replication drives change, according to the evolutionary yarn. So too, craft, marked by what David Pye calls “the workmanship of risk,” is driven by open-ended flexible practice: “The workmanship of risk is a realm where individuals, not entire industrial systems, hold the key to success.... every new beginning, every new product is a risk. Pye’s definition of ‘craft’ is not the extent to which an object is made by hand, but the extent to which it involves the workmanship of risk” (Press 263).

Anita Bruce and Aviva Alter — and the thousands of other women who have contributed to either the core Reef curated by the Institute For Figuring and its many satellite Reefs — are doing more than casting about for a biological metaphor to describe their experimental craft practice. Rather, they are gathering, appropriating, and weaving together the diverse

evolutionary yarns that have marked nineteenth and twentieth century biology — indiscriminately mixing the theories of Goethe, Oken, Haeckel, Thompson, Jacob, Eldredge, and Oyama, as well as assimilating trends towards formalizing and generalizing living form in mathematical biology, computational modeling, and Artificial Life. The result is a composite, materially-instantiated theory of biological change, one in which repetitive gestures recapitulate the protracted piecemeal depositions of polyps, and crafty improvisations offer tangible ways of understanding morphogenesis as consonant with their own craft practice. Their woolly corals are hybrid and freeform crafted objects; so too are their evolutionary yarns. This fact suggests that all constructive biologies — including, perhaps especially, those built in laboratories at MIT and the J. Craig Venter Institute, are material instantiations of sums of biological theories and knowledge. Constructive biologists may build new biological things to learn more about biology, but they also install their theories, apprehensions, faiths, and preconceptions into the objects they manufacture.

CONCLUSION

Curators Margaret and Christine Wertheim describe the reef as a “wooly testimony that now engages thousands of women the world over. Vast in scale, collective in construction, exquisitely detailed, the Crochet Reef is an unprecedented, hybridic, handicraft invocation of a natural wonder that has become, in itself, a new kind of wonder spawned from tens of thousands of hours of labor.” What is it about the Reef that makes it “a new kind of wonder?” Most concretely, this is a reference to the Great Barrier Reef, one of the wonders of the natural world. But more so, this claim to wonder aligns evolutionary change and its consequently diverse

bestiary of biological forms with the manual labor required to fabricate hundreds of thousands of crochet forms comprising what Wertheim calls an “ever-evolving crochet taxonomic tree of life” (2009) and a “complex woolen ecology” (unpublished manuscript). I first became aware of this association of biological evolution and human labor when I posed a question to Margaret while sitting in her home office, where she was showing me photos of her most recent exhibition. I asked her what all the projects she has curated through the Institute For Figuring have in common. She did not have to think about her answer; she had it ready at hand: what interests her, she said, is the connection between highly conceptual ideas and what she called “hard manual labor.” All the IFF’s projects combine esoteric concepts with thousand of hours of human labor, and it is this combination, in her words, that produces wonder. Wonder, she said, arises when one is able “to feel the crystallization of human time” when looking at an artifact. To look at the crocheted reef is to appreciate that tens of thousands of hours devoted to making it.³⁰ She compared this recognition to the wonder one feels when looking at the pyramids and being awestruck by the human labor that went into their construction (an analogy also made by Darwin when he marveled at coral reefs), but when looking at the crocheted Reef, she is struck by the “woman’s labor” put into its fabrication.³¹

³⁰ This astonishment calls to mind the sort of wonder tracked by Lorraine Daston and Katharine Park, who claim that prior to the seventeenth century, wonder was a protoscientific sensibility evoked by objects that were ambiguously both natural and artificial and hence resisted neat categorization (1998).

³¹ The comparison of coral reefs to pyramids, in fact, was not lost on Darwin either. During his voyages on the *Beagle*, he marveled,

We feel surprise when travelers tell us of the vast dimensions of the Pyramids and other great ruins, but how utterly insignificant are the greatest of these, when compared to these mountains of stone accumulated by the agency of various minute and tender animals! This is a wonder which does not at first strike the eye of the body, but, after reflection, the eye of reason (1839: 490-91).

The Reef is such a crystallization of hundreds of thousands of hours of labor performed by thousands of women, as the Great Barrier Reef, the largest structure in the world constructed by organisms, is the calcification of the concerted production of billions of coral polyps over the course of 20,000 years. When Margaret talks about the collective effort of the thousands of contributors to the Reef, her description of collaborative craft rhymes with marine biologists' narrative of the living reef. Stefan Helmreich, in suggesting coral as a Harawavian figure with which to grapple with questions of scale and context, quotes anthropologist Alfred Kroeber likening the social labor of coral depositing calcium carbonate to construct the Great Barrier Reef by infinitesimal degrees to the cultural production of humans.³² Perhaps coral provides an apt figure for the craft collective that spawned the Hyperbolic Crochet Coral Reef — its contributors number in the thousands, some contributors working prolifically to make dozens of pieces, but most contributors offering only one or a handful of crocheted objects to the Reef, building it piecemeal as a calcium carbonate reef would slowly accrete from the contributions of millions of polyps.³³

As Kroeber's analogy indicates, the comparison of cultural to biological production is nothing new. In fact, in the introduction to *The Division of Labor in Society*, Émile Durkheim

³² In "How Like a Reef," Helmreich identifies three figurations of coral reefs, tracking them from "their emergence as nineteenth-century architectures of curiosity, to their fashioning as twentieth-century polymorphs inviting immersive and fleshy encounter, to their twenty-first-century rewriting as nodes in global genetic networks" (forthcoming).

³³ The January 2009 issue of *Reef Encounter*, the Newsletter of the International Society for Reef Studies, cashed in on the parallels between crochet and calcium carbonate reefs when it described the proliferation of crocheted coral reefs in anthozoic terms: "A local reef is beginning in Sydney, Australia, one will be made in Arizona for inclusion in the Scottsdale show, and interest has been shown in Latvia. So just as living reefs send out spawn to produce new reefs, so also the Crochet Reef is spawning around the world" (2009).

compared the specialization of labor to biological evolution, arguing that the specialization of trade skills in society parallels the development of complex systems in an organism:

The law of the division of labour applies to organisms as well as to societies.... This discovery has had the result of not only enlarging enormously the field of action of the division of labour, but also of setting its origins back into an infinitely distant past, since it becomes almost contemporaneous with the coming of life upon earth. It is no longer a mere social institution whose roots lie in the intelligence and the will of men, but a general biological phenomenon, the conditions for which must seemingly be sought in the essential properties of organised matter. The division of labour in society appears no more than a special form of this general development. In conforming to this law societies apparently yield to a movement that arose long before they existed and which sweeps along in the same direction the whole of the living world (1964 [1893]: 2-3).

While such biological analogies are often mobilized to license, naturalize, or otherwise justify economic and labor relations, when Reef crafters compare the “evolution of life” to the “evolution of stitch,” something altogether different is at work. The analogy being drawn is not meant to argue prescriptively that social institutions should mimic biological phenomena, but instead to recast biology in a craft idiom — that evolution is materials-based, improvisational, and processual — and to enunciate that evolution may be made sensorially comprehensible and palpable by fabricating simulations of biotic forms. Biology, both the discipline and its object, is not here deployed as an analogy for labor, not its precedent nor its herald, but instead its product — biology is always something that is made, and something *in the making*.

Chapter 4: The Hyperbolic Crochet Coral Reef

Chapter 5. Screaming Yeast: Sonocytology, Cytoplasmic Milieus, and Cellular Subjectivities

That we have no ears to hear the music the spores shot off from basidia make obliges us to busy ourselves
microphonically.
—JOHN CAGE, *A Year from Monday* (1967)¹

INTRODUCTION

Saccharomyces cerevisiae, commonly known as yeast, is a unicellular fungus with a cell cycle similar to that of humans. The first eukaryote to have its genome fully sequenced and a standard model organism in biology research,² yeast is an organism that lends itself to multisensory experiences. It has been imaged extensively with light and atomic force microscopy, and anyone who has seen the bottom of a pint glass or walked past a bakery can speak to *Saccharomyces cerevisiae*'s olfactory and gustatory allure. It is fitting, then, that this species is also the first to have its cellular noises amplified and recorded.

Sonocytology, a recently developed technique within nanotechnology research, uses an atomic force microscope to record the vibrational movements of cell walls and amplifies these

¹ Cage 1967: 34, quoted in Kahn 1999: 195.

² The trajectory of twentieth-century biosciences and biotechnology is closely tied to yeast, an organism with significant economic uses. Given its abundance, economic and industrial significance, and the wealth of scientific information on it, yeast is often at the vanguard of new scientific experimentation. Yeast was instrumental in the early development of the biotechnology industry. It was present when the Royal Swedish Academy of Engineering Sciences coined the term *biotechnology* in 1943 to designate a new initiative of the academy — created at the urging of the secretary of the Brewing Research Society — that was devoted to pursuing biological solutions to wartime food, energy, and pharmaceutical shortages. Edy Velandar, a MIT-trained engineer, was named the director of the new section. He proposed the name *bioteknik* “to bring together applications which arise while one is learning to influence biological processes scientifically and exploit them technologically in an industrially organized activity, for example in industrial yeast cultivation, in the food industries for processing and improving the raw products as well as for the preparation and conservation of foodstuffs” (Velandar 1943: 1; quoted in Bud 1993: 96).

vibrations so that humans can hear them. Yeast cells vibrate approximately one thousand times per second. Humans can hear any vibration that has a periodicity in the range of twenty to twenty-thousand vibrations per second (Hz). The vibration of yeast cells is well within the frequency range of human hearing — in musical terms “about a C-sharp to D above middle C” — but the amplitude of their vibration is too low to be within normal hearing range (the cell wall is displaced only three nanometers each time it vibrates) (Wheeler 2004). By amplifying the vibrations of cells, researchers are essentially “turning up the volume” on cellular vibrations (ibid: 32). How are raw cellular vibrations converted into cellular sounds that scientists interpret as conveying meaningful information regarding the dynamism of cellular interiors? How do researchers become skilled in “listening to” and “touching” cells and organelles using scanning probe microscopes? What are the conditions that enable scientists to describe cells as actors capable of “speaking” or “screaming,” and how might listening to cellular sounds eventually change how scientists think about cells?

This chapter analyzes how sonification constitutes scientific objects and how scientists use sound to represent these scientific objects as subjects.³ While subjectivity implies the ability to speak to one’s conditions it also suggests that actors’ utterances are conditioned by epistemic and ideological regimes. Sonocytology renders ambiguous the distinction between cells *speaking* and cells being *spoken for*. Specifically, I attend to how raw sound is transformed into signals — that is, how scientists convert inchoate cellular vibrations into meaningful scientific data. In order to answer the question of how sound might alter the way in which scientists

³ A version of this chapter was originally published as an article (Roosth 2009). This piece drew on articles published in peer-reviewed scientific journals and in accounts by the popular press. This chapter is supplemented by later fieldwork conducted in the Gimzewski laboratories in 2008.

perceive and understand cellular activity, I first describe how sonocytology developed and how scientists and popular media have turned to metaphor in order to make sense of cellular noise. The sonification of cells, I argue, requires lab personnel to become skilled in apprehending (looking at, listening to, and touching) subcellular landscapes and soundscapes, which they accomplish through apprenticeships in building and wielding bespoke microscopes. I then focus on two epistemological effects of using sound scientifically to explore otherwise inaccessible spaces. The first concerns the ways we think of organisms in their environments and in relation to other organisms, and the second bears on the question of how we think about the interiority of an organism as a stage on which dynamic biological processes are performed.

Jim Gimzewski, a Distinguished Professor in the Department of Chemistry and Biochemistry at the University of California Los Angeles (UCLA), where he has taught since 2001, is best known for nanotechnology research he conducted while at the IBM Zurich Research Laboratory in Rüschlikon, Switzerland, where he built the highly publicized molecular abacus and molecular wheel (Cuberes et al. 1996, Gimzewski et al. 1998). A celebrity in the nanotech world, he has received numerous honors and prizes, including the prestigious Feynman Prize in Nanotechnology. During the course of my fieldwork in 2008, Gimzewski was at the helm of two laboratories on the UCLA campus: one in the Chemistry and Biochemistry Department, the other the California NanoSystems Institute Nano & Pico Characterization Core Facility. Five graduate students and four post-docs worked in his chemistry lab (2 women and 7 men); of those members, one post-doc also served as research director of the Core Facility at CNSI. The research his students now conduct is based on technology he helped develop in the

early 1980s while working at IBM Zurich. As a post-doctoral student and later a research team leader there, he pioneered the manufacture and use of scanning tunneling microscopes (STMs), which use van der Waals forces (induced intermolecular forces caused by neither covalent nor ionic bonds) generated between single atoms or molecules and tiny probes to generate three-dimensional topographies of nanoscale surfaces.⁴ Gerd Binnig and Heinrich Rohrer, his colleagues and supervisors at IBM Zurich, received the Nobel Prize in 1986 for designing the STM. The microscope he helped build at IBM is still in use in his UCLA laboratory.

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

⁴ The same microscopes are used for nanolithography and nanofabrication, as mechanical forces can “push” and “pull” single atoms or molecules into selected arrays or structures.

Since its manufacture in the 1980s, the AFM has become indispensable to nanotechnology work. While light microscopes cannot resolve objects smaller than half the length of a light wave, the AFM resolves this problem, which scientists term the Rayleigh limit, by using a probe to map the topology of the object being imaged. Borrowing Thomas Kuhn's phrasing, Gimzewski called the shift from light microscopy to probe microscopy a "major paradigm shift — rather than using lenses and waves, they were recording by feeling" (Gimzewski and Vesna 2003: 14).

Though both AFM and STM are examples of a broader category of microscopy called "scanning probe microscopy" (SPM), the techniques by which each microscope interfaces with a sample are quite different. Unlike STM, which operates in "tunneling mode" by measuring forces atoms and molecules exert on the probe across a small distance, in AFM, probes come much closer to sample surfaces, a technique researchers call "contact mode." Lab members compare both the AFM and STM reading the topology of a microscopic surface to a blind person running his finger over a line of braille (Gimzewski and Vesna 2003: 10) [Figure 5.1]. As a tiny cantilever (its tip is less than ten nanometers wide) is displaced by the surface of an object, a piezoelectric crystal converts nanomechanical motion into voltage, creating a map of the surface. However, instead of dragging a probe over the surface of a sample, Gimzewski and Pelling held the AFM probe stationary on the surface of a yeast cell so that the oscillations of its cell wall could be traced, a technique Gimzewski compares to "using your finger to feel a pulse" (Anon. 2004a).

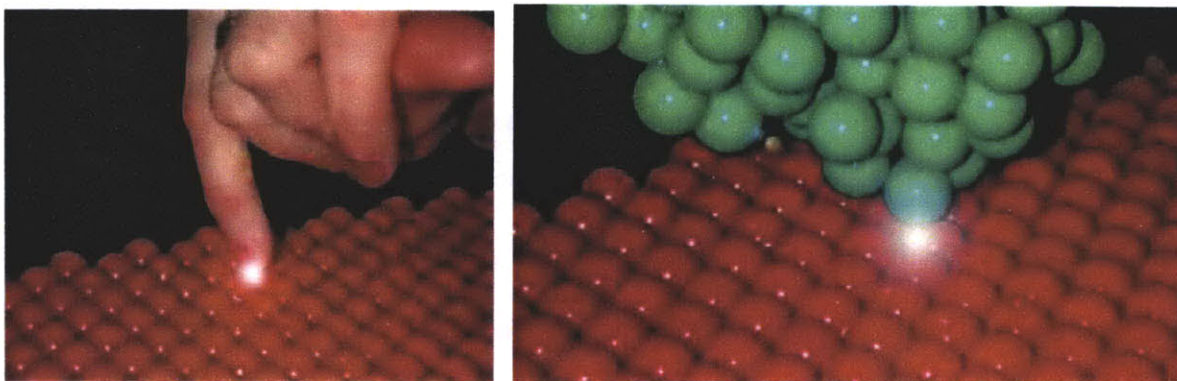


Figure 5.1. The comparison of SPM to touch, from Gimzewski and Vesna 2003. The original caption explains, “The gentle touch of a nanofinger is shown in (a) where if the human finger was shrunk by about ten millions times it would be able to feel atoms represented here by spheres 1 cm in diameter. If the interaction between tip and sample decays sufficiently rapidly on the atomic scale, only the two atoms that are closest to each other are able to ‘feel’ each other as shown in (b) where the human finger is replaced by an atomically sharp tip. Binnig and Rohrer (1999) inspired this explanation of the STM” (ibid).

Yeast cells, about five microns in length, have walls much more rigid than most mammalian cells, making it easier to rest a microscopic probe on their surface in order to detect cellular vibrations. Gimzewski discovered that yeast cells vibrated rhythmically and that the periodicity of the vibration was within the range of human hearing.⁵ Using a freeware program, he converted the vibrations recorded by the AFM into a sound file. Gimzewski claims that sonocytology is preferable to other techniques for rendering cellular interiors because it is “not invasive and does not depend on the use of chemical dyes, fluorescent markers, or quantum dots” (Pelling et al. 2004: 1150). He argues that the naturally occurring synchronized movement of motor proteins “cannot be observed by traditional cytological methods” (ibid: 1150) and are

⁵ At the time, one of the questions Gimzewski was interested in answering was whether the vibrations of “molecular motors” inside yeast cells synchronize with one another. Gimzewski’s interest was inspired by Christiaan Huygens’s study of the “odd sympathy” between the pendulums of clocks mounted on the same wall. Although he never found evidence of subcellular proteinaceous coupled oscillations, an unlikely trio expressed interest in this research: the Maharishi Mahesh Yogi, practitioners of traditional Chinese medicine, and the defense company Lockheed Martin. Gimzewski hopes to return to this investigation some day.

“too small and fast to be seen on video” (Anon. 2004b).

How do acoustic technologies change what it means for something to be audible, given that sound is by definition a vibration that can be heard by an organism? Jonathan Sterne defines sound as “a product of the human senses and not a thing in the world apart from humans” (2003: 11). Extending Sterne’s definition beyond the hominid, under the rubric of sound I include any vibration perceptible to any organism; that is, sound is the sum total of Michel Serres’s “global tympanum” — a soundscape filled with “waves rather than spaces” that “moulds and indents” listening organisms (1998: 180-1; quoted in Connor 2005: 324). A vibration is not necessarily audible, and sounds are not inherently meaningful. Only mechanical oscillations within a small range of frequency and amplitude are audible without technical manipulation.

Sound is any vibration within the range of an organism’s hearing or, since the advent of acoustic technologies, of an organism-acoustic machine assemblage. Because sound is necessarily related to a biological sensorium and assumes a tuned-in body, it has a semiotic component that is parsed in historically and socially specific contexts. If a signal is not deemed meaningful by a listening body then it is *noise* — “irrelevant or superfluous information” that can interfere with the transmission of information. A *signal*, in contrast, is a sound that a listener regards “as conveying information about the source from which it comes” (OED).

Cyrus Mody, in his ethnographic account of how sound structures laboratory experimentation and contributes to the construction of scientific knowledge, argues that the

separation of good sound from acoustic contamination is an evolving process that is both contingent and context specific (2005).⁶ Apart from vibrations, which refer to a purely physical phenomenon, *sound*, *noise*, *signal*, *music*, *voice*, and *scream* each assume a listener who can make a judgment as to the ontology of an acoustic resonance. A listener designates a sound as *music* if he or she judges that someone composed it to be rhythmic, aesthetically pleasing, or otherwise expressive. Claiming that a sound is a *voice* imbues the sound's source with the agency to utter sounds that convey information. A *scream* is inarticulate speech made by a human to express extreme pleasure or pain. Nonhuman animals are rarely described as screaming; they screech, squeal, yelp, or howl. Attending to how cellular oscillations are alternately described as sound, noise, signals, music, singing, or speaking reveals the ways in which listeners interpret cellular agency and subjectivity.

Much in science studies has been written on the role of visualization in scientific research. Indeed, visual concerns and metaphors are central to the theories used in Science and Technology Studies; STS scholars often speak of Bruno Latour and Steve Woolgar's "inscription devices" (1986), Latour's "drawing things together" (1990), David Kaiser's "drawing theories apart" (2005), Jacques Derrida's "traces" (1993 [1976]) Donna Haraway's "god's eye view from nowhere" (1988), Ian Hacking's *homo depictor* (1983), and Walter Benjamin's unconscious optics (1969).⁷ In addition, scholars have learned to think about *panopticism* and the anatomy of

⁶ Henning Schmidgen provides an earlier example of the disruption of laboratory work by sound. Adolphe Hirsch, director of the Neuchâtel observatory in Switzerland, began to experiment with using chronoscopes to measure the reaction time of astronomers in 1861. Throughout his experiments he was disturbed by the humming of his own lab instruments and by the ringing of bells outside. Hirsch "saw his efforts to precisely determine and communicate time threatened by another, more ancient system for communicating time" (2003: 259–60).

⁷ For more examples of ocularcentric terminology in STS, see Mody 2005.

power from Foucault, feminist and psychoanalytic theories have introduced the issue of the gaze, and postcolonial studies has exported the I/eye.

In contrast, with the exception of recent analyses of the scientific uses of space sounds, underwater sounds, and laboratory sounds, acoustic technology in scientific research until a short time ago had been understudied and undertheorized by STS scholars.⁸ An important special issue of *Social Studies of Science* does not examine sound as scientific data, though the editors do open up a critical dialogue between STS and sound studies, emphasizing that STS can offer “a focus on the materiality of sound, its embeddedness not only in history, society, and culture, but also in science and technology and its machines and ways of knowing and interacting” (Pinch and Bijsterveld 2004: 636). In his study of acoustic contamination in laboratory science, Mody shows that researchers diagnose problems in their microscopes by listening to them, a practice that functions as an auditory transmission of tacit knowledge that imparts a more “embodied interaction with the instrument” (2005: 188). In the end, he calls for a more anthropologically motivated thick description of the status of all the senses in laboratory practice. While Mody examines how acoustic contamination dictates the structure of experimentation in laboratories, I attend to the status of sound as primary scientific data — sound as scientific signal — rather than noise. Understanding the separation of meaningful data from experimental contamination as a culturally determined judgment, I examine how scientists in Gimzewski’s lab make sense of cellular noise. Parsing cellular signals from noise, I argue, is determined by researchers’

⁸ On the scientific use of space sounds, see Johnson and Lecusay 2005; on underwater sounds, see Helmreich 2007, 2010; on laboratory sounds, see Mody 2005; on the design of audio technology, see Downes 2009; on musical instruments in early twentieth century biophysiology experiments, see Kursell 2006; on the history of noise abatement strategies, see Bijsterveld 2008.

understanding of cells as subjects capable of speaking to their conditions.

What kinds of new soundscapes are created by acoustic technologies and how are they listened to, explored, and made sense of by scientists through the mediation of technology?⁹ Drawing on my own ethnographic work learning to tinker with and use scanning probe microscopes, I claim that mastering how to “listen to” and “feel” biological samples requires apprenticeship in auditory and tactile technique. In particular, practitioners must learn how to orient their own bodies in relation to their machines, even as they are encouraged to ignore technical mediations in favor of imagining a direct experience of subvisible biological things. Learning how to use a scanning probe microscope requires that scientists learn to ignore sometimes its mediating presence — to construct a shared biological milieu — when making sense of data. In explicating how sound affects the way we understand cellular interiors, I then employ Georges Canguilhem’s use of the concept of milieu — an array of decentered and mutually influential relations between an organism and its surrounding environment — to argue that sound clues us into the material situatedness of cellular life (1952). By drawing listeners into the environment of its source, sound creates a soundscape in which the different milieus of people and cells can resonate. Finally, by considering the diverse meanings of transduction — the conversion of a signal from one medium to another — I explore how sound travels through different material environments and how it is converted into scientific information.

⁹ *Soundscape* is a term coined by R. Murray Schafer to emphasize the ecology of sound (1969). Since then, it has become widespread in sound studies, although its meaning is not clearly defined and its use sometimes inconsistent. By recalling “landscape,” it “offer[s] a way of describing the relationship between sound and place” and “continues to resonate because it suggests the relationship between sound and context truly *does* matter to scholars of sound” (Kelman 2010: 215, 230; emphasis in the original).

After addressing the influence of acoustics on the understanding of cellular milieus, I turn my attention to the understanding of cellular temporality, asserting that sound makes it possible to access *in situ* the internal biological processes of bodies and cells, allowing us to understand bodies and cells *in time* and *in context*. While STS scholars have critiqued science for reducing subjects to experimental objects, I examine how scientists make sense of cellular noises and more specifically how sonification constructs a particular form of technologically and socially mediated cellular subjectivity.

LISTENING TO CELLS

When Gimzewski and Pelling examined the data recorded by the AFM and realized that yeast vibrate regularly, they went online and downloaded Awave Audio, a computer program that could convert the vertical deflection data into a WAV file.¹⁰ When they ran the program on the lab computer and turned on the speakers an ethereal noise filled the laboratory.¹¹ Beginning to experiment with the noise produced by yeast, they recorded the vibrations yeast made at different temperatures and in different solutions. Adding sodium azide, a chemical that inhibits cellular metabolism, to the yeast caused a noise that sounded like radio static. Gimzewski believes this sound is an indexical representation of the Brownian motion of molecules, since sodium azide stops all ATP-driven nanomechanical activity. When they doused the yeast in alcohol, the pitch

¹⁰ “We took the AFM vertical deflection data straight off the photodiode and logged it as a 16-bit ASCII text file, which was basically one column of vertical deflection values. The time between each value is then $1/f$, where f is the sample frequency (typically 10kHz or more). Anyway, both Awave and SpectraPRO allowed us to just import these ASCII files with the appropriate sampling rate and save them as WAV. Since they are oscillatory they are just like any electronic sound file. The only manipulation was normalization to 12–16 dB which made the files louder. Otherwise all the frequency information and relative amplitude modulation was retained” (Pelling, personal communication, 20 Nov. 2006).

¹¹ To listen to recordings of cellular sounds, hear www.darksideofcell.info

of the vibration increased. In an interview, Gimzewski claimed that: “it screams. It doesn’t like it. Of course, yeast produces alcohol as in beer production, but if you put strong alcohol like Absolut vodka on it, if you like, then it screams. It screams. It doesn’t like it.” He speculates that this “screaming” is the sound of molecular pumps working overtime to expel the alcohol (Anon. 2004a).

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

Sonocytology, and Gimzewski's characterization of his technique in particular, is saturated with tropes borrowed from "Eastern" religions, and the notion of biological vibrations has struck a chord with many representatives of such countercultural movements. When Gimzewski and Pelling published their findings in *Science*, representatives of the Maharishi Mahesh Yogi approached them, thinking that they had "discovered 'the language of life'" (Thompson 2004: 82).¹² Indeed, the bookshelves of Gimzewski's office are crowded with books sent to him by people who read about sonocytology in the popular press and think that it might be one technique with which to scientifically validate their particular New Age philosophy: traditional Chinese medicine, extrasensory perception (ESP), Zen Buddhism, yoga, meditative auras, biofeedback, etc. For his part, Gimzewski practices Kundalini yoga and has invited Tibetan monks from the Ghaden Lhopa Khangsten Monastery into his laboratory to meditate beside the scanning tunneling microscope and to compose sand mandalas. He hopes sonocytology, by registering biotic vibrations, will verify the "subtle phenomena" he considers to be central to multiple non-Western medical, mystical, and spiritual traditions, among them the principles of *qi* and *chakra*. More so, he believes that biological vibrations are at the heart of disparate theories of life energies or forces posited by diverse "Eastern" traditions. Zen Buddhist philosophy also inflects the way Gimzewski describes nanotechnology, given the quantum forces operating at nanoscales, and the fact that much of what is apparent to the human eye, such as color, substance, and form, reveals itself as what Gimzewski terms an "illusion — a beautiful

¹² Lily Kay notes that "the language of life" is a metaphor imbued with "operational force" that, although having a long history in Western culture, was made literal and given scientific legitimacy by linguistics only in the 1950s and 1960s (2000: 1). In a Derridian turn, sonocytology extends the linguistic metaphor of life by listening for uttered signs rather than decoding written words.

illusion” when explored by probe microscopy: “It is as if the doors of perception have suddenly opened and the [light] microscope’s imperfection of truly representing object form forces us to question our traditional (Western) values of reality” (Gimzewski and Vesna 2003: 12). Having reached adulthood at the height of the Euro-American preoccupation with “Eastern” traditions, it is not surprising that Gimzewski is, to borrow countercultural parlance, “tuned in” to such doctrines, even as he divorces it from the historical and cultural contexts that situate them.¹³

The sounds made by yeast also provoked flights of metaphorical fancy as scientists and journalists alike struggled to find words to describe something new in familiar terms. Popular press articles on Gimzewski’s technique have likened the sound to the whistling of singing whales and have compared the AFM to a microphone, a new musical instrument, or, as Pelling suggested, a record needle.¹⁴ Gimzewski told reporters that if yeast were the size of humans

¹³ Since the Countercultural movements of the 1960s and 1970s, the notion that science is compatible with “Eastern” philosophies has become increasingly common, as exemplified by books like Fritjof Capra’s *The Tao of Physics*. Such rhetoric was reshaped in a *Nature* review of Gimzewski’s collaboration with Tibetan monks:

The mandala-makers and the nanoscientists share the wonder of scale, involving countless parts to compose the ordered whole. We can sense the way in which religious contemplation of a time-honoured kind and modern technological science are, in their different ways, reaching out to the edges of infinity. This is the aesthetic realm of the sublime. It is inhabited by all those who stand in awe at the wonder of the Universe and in thrall to the varied mental capacities we use to make sense of what we see and feel (Kemp 2007: 146).

In his forthcoming history of how quantum theory flourished in the “hazy, bong-filled excesses of the 1970s New Age movement,” David Kaiser reminds readers that there is a long history of exploring parapsychological, mystical, and occult phenomena from the vantage of scientific respectability, dating at least to “mesmerism in the 1770s and spiritualism in the 1870s,” followed by explorations of “Eastern” philosophy and *psi* phenomena in the 1970s (forthcoming). For another account of how “Eastern” philosophy can infuse scientists’ accounts of their work, see Helmreich 1997.

¹⁴ For singing whales, see Lurie 2004; for the microphone analogy, see Jaffe 2004: 50; on the comparison to a new musical instrument, see www.darksideofcell.info/zkminterview10.mov; for the comparison to a record needle, see Wheeler 2004. Gimzewski also compares STM to a record needle: “the STM uses a form of quantum sensing called electron tunneling to ‘feel’ atoms one by one, much as the needle of a phonograph picks up information embedded in the groove of an LP record” (2008: 260). Comparing the AFM to a record needle raises the question of whether a vibration constitutes a signal by virtue of its audibility. Rainer Maria Rilke, in “Primal Sound” (1919), asks “what variety of lines, then, occurring anywhere, could one not put under the needle [of a phonograph] and try out? Is there any contour that one could not, in a sense, complete in this way and then experience it, as it makes itself felt, thus transformed, in another field of sense?” (quoted in Kittler 1999: 41). Kittler responds to Rilke’s question by claiming that “before [Rilke], nobody had ever suggested to decode a trace that nobody had encoded and that encoded nothing” (ibid: 44).

their sounds would be closer to the volume of ordinary conversation than of loud music and that “if you were to shrink down to the cell’s size, it would be like holding a transistor radio to your ear” (Jaffe 2004: 50). Lab members are also prone to thinking about their microscopes as audio technologies. Many of them have been in or continue to perform in bands — during my stay in the lab, two grad students performed in bands, others played music as a hobby, and at least one graduating PhD confided that he had independently made music using both nuclear magnetic resonance recordings and the decimal notation of *pi*. When Margaret Wertheim (Chapter 4) described Gimzewski in her LA Weekly column as someone who “might easily be mistaken for a refugee from an aging British rock band” (2003), she was not far off from the truth — before working at IBM in the 1970s, Gimzewski had indeed been a member of a British rock outfit called Attention Deficit. And while graduate students would spend full days staring at computer screens, trying to make sense of data gleaned from AFM and STM scans — that is, as they separated “sound” from “noise” — they also immersed themselves in very loud noise, often in the form of pop rock and industrial metal Internet radio stations. When Gimzewski complained to me that one of his students spent “all day” with “that noise on the computer,” I was unsure whether he was referring to his student’s data or his musical tastes.

While the sounds produced are conversions of surface vibrations of yeast cells, Gimzewski believes these sounds provide access to the workings of the cellular interior by indexically signifying cellular metabolism and movement.¹⁵ Describing the technique he

¹⁵ Charles Sanders Peirce defines three types of signs: the icon, the index, and the symbol. The index is a sign that has some kind of physical relationship to its referent. Or, as Peirce explains more lyrically: “Anything which focuses the attention is an indication. Anything which startles us is an indication, in so far as it marks the junction between two portions of experience” (1998 [1894]: vol. 2: 8).

developed, Gimzewski says: “We gently touch a cell, a living cell and we listen.... They actually produce a kind of music and you can hear it” (Lurie 2004). He says the music made by the cell is “amazing” (Anon. 2004a) and “beautiful” (Thompson 2004: 82). This characterization as music is predicated upon a definition of sound as something audible not only to the ear but to the ear with the aid of technical amplification. Like Cage’s basidia spores, yeast are already making music; we just have to heed Cage’s advice and “busy ourselves microphonically” in order to hear it. Calling these sounds music actually casts the organism as composer, extending authorship and artfulness into the natural world.

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

Gimzewski believes that sonocytology has potential diagnostic applications because cancerous cells metabolize adenosine triphosphate (ATP) more quickly and therefore vibrate at a higher frequency than noncancerous cells. His ultimate goal is for clinicians to be able to detect cancer at an early stage by listening to cells. One obstacle to a medical application of sonocytology is the fact that mammalian cell membranes are much less rigid than the cell walls of yeast. However, exploiting the softness of metastatic cells, Gimzewski, working with

pathologists at UCLA's Jonsson Comprehensive Cancer Center, is now using probe microscopy to try to diagnose cancer cells by their softness (Cross et al. 2007). In conversation, Gimzewski compared this research project to selecting fruits and vegetables by gently squeezing them, avoiding the squashy ones.¹⁶ Gimzewski also collaborates with Michael Teitell, an immunologist who develops animal models for lymphomas (Wertheim 2003: 33). Teitell exposes human and mouse osteocytes to chemical mutagens, and Gimzewski tries to identify which cells are cancerous using sonocytology.

Cellular sounds are not meaningful to the cells, but they could be made meaningful through human audition. Other scientists have suggested that the vibrations picked up by the AFM are signals the cells use to communicate with one another. Kerry Bloom, a mycologist at the University of North Carolina, points out that it was a “big surprise when people played rock music to plants, and there was a chemical change inside the cell of the plant when you played the [Rolling] Stones at high volume. And so now I would argue the same thing with anything with a cell wall. Now the expectation is some physical output that can be another level of signaling” (Anon. 2004a). Inscription devices turn occurrences into events, and the AFM turns sonic and informatic noise into a meaningful message.¹⁷ In attempting to make sense of cellular noise, Bloom speaks on the yeast's behalf.

¹⁶ In a 2007 press release, Gimzewski continued his fruity metaphor: “You look at two tomatoes in the supermarket and both are red. One is rotten, but it looks normal.... If you pick up the tomatoes and feel them, it's easy to figure out which one is rotten. We're doing the same thing. We're poking and quantitatively measuring the softness of the cells.”

¹⁷ The distinction between occurrences and events is one of awareness; the act of looking or listening turns something that merely happens into something more momentous. Benjamin coined the term *unconscious optics* to refer to the camera's ability to bring a previously unnoticed movement to our conscious attention by substituting an “unconsciously penetrated space... for a space consciously explored by man” (1969: 236–37). Perhaps we could think of sonocytology as a technique of unconscious acoustics with which vibrations too small to be heard are brought to our attention.

SKILLED APPREHENSION: LEARNING TO BE IN “CONTACT MODE”

The heterogeneous machinic infrastructures and social conditions that render biological soundscapes audible and sensible are many. Sonocytologists analogize their machines to sensory capacities: SPMs, they told me, were like human ears, fingers, and noses, and learning how to wield these sensory prosthetics, I found, required learning how to build them. Jonathan Sterne has argued that techniques of listening precede audio technologies, such that dispositions of skilled listening crystallize in sound reproduction technologies that extend and focus hearing (2003). I would complicate Sterne’s account by suggesting that the process of learning to listen or touch scientifically — what, after anthropologist Cristina Grasseni’s “skilled vision” (2004), I would characterize as “skilled audition,” or more broadly, “skilled apprehension” — is inculcated and sharpened by the work of building the machinery that mediates and modulates how lab members listen to and touch cells, organelles, and other living things. If soundscapes are forged and fabricated out of material and social infrastructures, then central to this work is the literal and figurative honing of the sensorium to such soundscapes. Learning how to incline one’s ear or put a hand to the cellular means first learning how to put together, take apart, and work with the prosthetics that make such sensing possible.

When I arrived at Gimzewski’s lab, I was most interested in how researchers learn how to listen to cells; I was surprised to discover that learning to listen is inseparable from learning how to work with SPMs to “touch” cells and organelles. On my second day after joining the lab and telling lab members that I was interested in examining non-visual approaches to biology, Greg, a

post-doc in the lab, put me to work refurbishing an ultrahigh vacuum (UHV) STM, a piece of equipment that, the first time I saw it, reminded me of a submersible from Jules Verne, towering over me in a darkened room, its reinforced metal arms punctuated by portholes circumscribed with bolts. Icy flumes of liquid nitrogen eddied from spiraling lengths of copper tubing snaking out of the machine, and the cables running between it and the computers in the adjacent lab were held together by what Greg described as a “goopy mess” of duct tape. My job on the first day was measuring lengths of cable, then using a razor blade and calipers to strip the cable before adding plastic insulation. Over the course of several weeks, my jobs became increasingly difficult, and required increasing levels of skill.¹⁸ As we worked, Greg told me that in order to be a successful scientist, one must learn the “little skills” needed to do good lab work. Such skills, he said, should be imparted from senior grad students and postdocs to younger lab members, and, he said, if a grad student does not learn these skills, he or she is likely to “graduate in shame,” that is, without a publication. When Greg arrived in the laboratory, the STM “tradition,” as he put it, was “dropped” twice, the first time when a graduate student began working with an STM inherited from scientists at IBM. This grad student “had to feel around in the dark” to learn how to operate the STM, and “wasted a lot of time trying to learn via trial and error.” In response, Gimzewski called in colleagues who knew how to use the STM to visit the lab for a month at a time to teach his grad students how to use the machine. The “tradition” was lost again when that

¹⁸ Although I did not stay in the lab long enough for my time there to be regarded as apprenticeship in the full sense of the term, the work I did progressed in a manner akin to what Lave and Wenger have called “legitimate peripheral participation,” whereby amateurs acquire skill via on-the-job training that gradually moves from peripheral to central activities (1991).

student graduated before Greg arrived in the lab.¹⁹

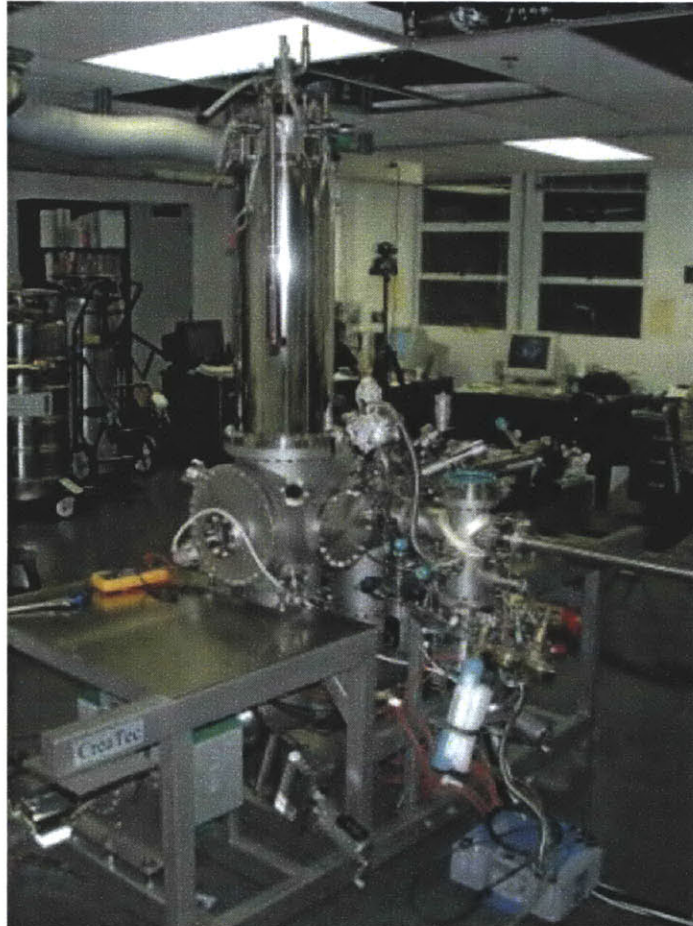


Figure 5.2. A Scanning Tunneling Microscope in Gimzewski’s CNSI Core Facility at UCLA.

Photo: James Gimzewski.

Greg decided to apprentice me, calling me “his grad student” and teaching me how to work on the microscope and use it to run samples. When other graduate students dropped by and

¹⁹ Greg elaborated on this point in a later conversation, offering an excellent encapsulation of tacit knowledge: “The transfer of knowledge for the operation of a very complex instrument is more of an oral tradition — akin to storytelling, that degrades a great deal if the two consecutive generations do not meet. It’s all the little details that one thinks are not important enough or would be too tedious to put down on paper that gets [sic] lost” (personal communication, 19 July 2010).

asked Greg what he had me doing, he told them that he was “turning [me] into a UHV expert,” the acronym referring to ultrahigh-vacuum microscopy (UHV being pressures lower than 10^{-7} pascals). After two weeks in the lab, Greg began teaching me how to build a tungsten filament for the microscope. Though tungsten filaments can be purchased from lab equipment supply companies, building one from available parts is much less expensive. From boxfuls of equipment left over from previous experiments, we gathered the materials from which to build the filament: tungsten wire, a paperclip, scraps of metal, a piece of ceramic, and a welding gun, pliers, and soldering iron. He referred to this routine and hands-on work, which I did sitting cross-legged on the ground in front of the STM, as “arts and crafts.” Over the course of my time in the lab, I graduated from simple tasks such as building filaments, replacing copper rings, and using ammeters, to rewiring arms of the STM, and later helping to disassemble and rebuild components of a modified hybrid STM/AFM, as well as learning to run samples [Figure 5.2].

When I asked post-docs and grad students why Gimzewski insists that lab members build their AFMs and STMs rather than buying them, they explained that it is both for financial considerations and to gain a better sense of the machine — this way, they said, they will not just be able to use the microscope, but also understand *how* the microscope works, and have a mastery of it such that if the equipment breaks, they can fix it. Further, they will know how to adapt and adjust the machine to scan particular kinds of samples and towards gathering different kinds of data. This tinkering approach to SPM and the virtuosity it affords is what enabled Gimzewski and Pelling to break with the AFM protocol, holding the cantilever stationary to register cellular vibrations rather than using the standard method of mapping cellular

topographies. As one graduate student who was working on building a new AFM (which he kept protected in a wooden box onto which he had affixed pink glitter glue and stickers), explained to me, building your own microscope gives you the “flexibility” to swap out parts for particular imaging experiments, tailoring the machine to its substrate, swapping out “fingers”²⁰ for “ears”²¹ for “noses.”²²

Whereas cells rendered audible are described using musical metaphors such as record needles and microphones, researchers overwhelmingly compared STM and AFM-mapped surfaces using cartographic metaphors, comparing samples to new or alien landscapes to be plotted with tiny cantilevers. While looking at a terrain of polystyrene beads mapped with the AFM, Gimzewski recalled the first time he saw a buckyball, while working at IBM in the 1980s. At the time, he was overwhelmed by the fact that he was seeing something no one had seen before, and said that as he zoomed in, closer and closer, he felt that he was “exploring new spaces.” One of his colleagues at the time likened the experience to European seafarers discovering Australia and mapping the continent. Other lab members made similar comparisons: one graduate student working to make a nanoscopically flat substrate on which to deposit DNA was frustrated by a deep fissure in her substrate, which she called the “Grand Canyon,” hypothesizing that hydrofluoric acid acted like a “river” eroding the sheet of mica and forming “terraces” along the canyon’s interior. While looking at AFM scans of antibodies, Gimzewski

²⁰ STMs and standard AFMs

²¹ Stationary AFMs

²² Arrayed AFM cantilevers on a silica drum, a machine Gimzewski has developed which can sense 28 different peach flavors and which, one researcher told me, is an improvement on trained human noses because it “never catches a cold,” nor is it subject to the vagaries of age or weather.

marveled that the fuzzily rendered immunoglobulins on the computer screen looked like images of Martian landscapes.²³

The comparison of microscopic and nanoscales to foreign terrain is a common trope in twentieth century microscopy, as Nicolas Rasmussen has demonstrated in his history of electron microscopy.²⁴ When microscopists “[experience] themselves transported by the instrument to an alien landscape” (1997: 232), it denotes the extent to which researchers “dwell in” or interiorize (Polanyi 1969) their STMs as extensions of their own bodily sensoria. Gimzewski compared this experience of “indwelling” in his “tactile sensing instrument[s]” to driving a car, a comparison that also dates to electron microscopy in the 1930s and 1940s (Rasmussen 1997).²⁵ As he put it, “an unconscious connection to the atomic world quickly becomes automatic to researchers who spend long periods of time in front of their STMs. This inescapable reaction is much like driving a car — hand, foot, eye, and machine coordination becomes automated” (Gimzewski and Vesna 2003: 11).

Researchers’ embodiment of these sensory prosthetics is further evidenced by the manner

²³ The comparison of nanoscale surfaces to foreign terrains fosters the analogy of SPMs to vehicles, usually cars, which transport researchers to new locales, and working on the microscopes is compared to shop work (see footnote 25). When, while trying to run a sample, I lowered the cantilever too quickly and collided with the sample, I was chided for “crashing.”

²⁴ Researchers are not the only ones who make the analogy of nanoscopic things to “landscapes.” Note that the notion of “soundscape,” by which I mean a constructed sonic milieu, also perpetuates the topographic metaphor.

²⁵ The car-microscope analogy was particularly potent for one grad student in the lab, who raced cars and worked in a machine shop while in high school and still works on cars. A previous lab member, knowing how much he enjoyed garage work, recommended him to Gimzewski when Gimzewski was looking for someone to build a new AFM for the lab. As the grad student told me in conversation, at the time he “had no idea what an AFM was,” but knew a little about STMs, and thought it would be “fun” to build one. Watching him running samples in contact mode, alone in front of his computer screen with loud music blaring from his speakers, it was easy to picture him at the wheel of a race car.

in which they narrate their scanning work as something in which their body is positioned, such that the motive force, as they describe it, comes from *them* — their bodies, fingers, and ears — rather than the cantilevers that they manipulate. An example illustrates this point. When an unidentifiable artifact appeared in one grad student's AFM images of an organelle called an exosome, Gimzewski and he sat in front of the computer, trying to figure out what the doughnut-shaped object might be. Gimzewski told the student to “press harder” on it, and the grad student moved the cantilever closer to the sample before scanning it again. The resulting scan showed a much larger object than the previous scan. Gimzewski commented that they must be putting it under “incredible pressure.” They continued to bear down on the object, and it swelled to fill the computer monitor. At this point, the graduate student wanted to stop, worrying that the pressure would ruin the tip of his cantilever, but Gimzewski insisted they continue. As they alternately pressed harder and retracted the tip, the object would expand and contract, prompting the grad student to mutter, “son of a bitch, we can't kill this thing.” Sitting behind them, I interjected, asking whether the change in the object's size was because of the pressure being put on it, like a balloon, and Gimzewski reminded me that even though the map on the monitor “looks like an image, we aren't really *seeing* it.... This isn't something we are seeing, this is something we are touching, so really we are *right there*. We are right there above it.” Both synaesthetic and projective, the skilled apprehension Gimzewski here articulated reminded me that the work of learning to use an AFM also entailed working to forget the spatial intuitions of researchers' daily experience, to create a shared space in which it is plausible to “touch” and “listen to” biological things. Learning to use scanning probe microscopes does not, as Sterne has suggested of audio technologies, crystallize the sensorium in technologies that extend or amplify it, but rather joins

habituated technique to technology in order to invest subvisible biological objects with texture, consistency, and elasticity. “Dwelling in” and merging cybernetically with their AFM, researchers touch and hover “right there above” cells and organelles, losing track of the technical conditions that allow them to span embodied and subcellular scales.

Learning the skilled apprehension of STM and AFM also gets worked out in conversation, as researchers debate what really counts as “seeing,” “touching,” and “hearing” things subvisible. When I asked about the difference between AFM and STM microscopy, one grad student told me that the AFM “touches” the sample, whereas the STM does not. A second grad student amended this definition, asking rhetorically, “What is touch?” The AFM does not really touch the sample either, as there is always an atomic gap between cantilever and sample, the AFM “just gets closer” than the STM does.²⁶ This characterization was echoed by a post-doc at Gimzewski’s California NanoSystems Institute (CNSI), who told me that both AFMs and STMs have cantilevers that work like a “finger” that comes closer to or further from a sample, and a piezoelectric crystal, which is a transducer or “nervous system” — “a way to know what you’re feeling,” because it proprioceptively detects the finger’s position.

Further, practitioners must learn to calibrate their perceptions to the nanoscale, adjusting

²⁶ These lab discussions, of which I heard many, conflate the embodied, subjective experience of touch with the nanoscale — the feeling registered as touch or pressure always occurs across a gap much greater than the nanoscopic gap between cantilevers and substrates. Nonetheless, the analogy of probes to fingers encourages researchers to worry over how close two atoms must be before they can be described as “touching.” Colin Milburn reports a similar collapse of the nanoscopic and the embodied scales in nanotechnology: “Depriving human perception a privileged spectatorial position from which to take control of its imagined environment, nanovision problematizes the relationship between the observer and the observed, the human and the extrahuman, the macroscale and the nanoscale.... distance vanishes in the haptic space of closeness and molecular intimacy” (2008: 104).

how they think about things “small” and “large.” Toward the end of my time in Gimzewski’s lab, I sat with him and a post-doc in front of a computer screen at CNSI looking at polystyrene beads hexagonally arrayed. The beads, Gimzewski told me, were about 10 micrometers in diameter, about 1/5 the width of a human hair. Having gotten used to nanometer-scale objects, I exclaimed, “Oh! So this is really quite big.” Gimzewski and the post-doc found my comment enormously funny, and Gimzewski joked that I had “finally learned to think the way [they] do,” before turning to me to say, “now you’re part of the group, because you know what ‘small’ really means.” Admission as a sonocytologist demands recalibrating and reorienting one’s body towards subvisible substrates, both feeling and gaining a feel for otherwise inaccessible spaces. The work of doing so constructs a shared milieu in which cells are audible and palpable to researchers.

ACOUSTIC MILIEUS

Emily Thompson defines a soundscape as “simultaneously a physical environment and a way of perceiving that environment; it is both a world and a culture constructed to make sense of that world.” Bound up in the process of turning sound into data is the listener’s culture, the environment in which the sound reverberates, and “the material objects” within that environment “that create, and sometimes destroy, those sounds” (Thompson 2002: 1). That is, a listener is both acoustically and culturally immersed in soundscapes.²⁷ But how does sound condition an organism’s environment, and how does that environment affect which sounds count as signals and which are merely noise? Listening to cellular noises attunes lab members to the way each

²⁷ Helmreich uses multiple registers of immersion and transduction to anchor his ethnographic account of his descent in Alvin, an underwater submersible. Immersion can alternately be used to describe being “in water, sound, or the medium of culture” (2007: 602).

cell is embedded in, and in mutual relation to, its microenvironment. Symmetrically, just as cellular noises draw attention to a cell's immersion in extracellular environments (in this case, the constructed environment of the laboratory), the interpretation of cellular noise is embedded in the listener's culture, as well as in their skilled apprehension of biological sounds and textures, and their embodied orientations towards their microscopes. By tying cellular and cultural immersion together, we can hear how listening to cells creates a space in which cellular and human milieus resonate.

Gimzewski's AFM is housed in a special darkened noise-free room, inside a thermally, acoustically, and electrically isolated chamber lined with foil on a vibration-free platform suspended in air. The care taken in isolating the AFM from any vibration is necessary in order to verify that the vibrations recorded are due to cellular activity and not to any external noise (here I mean noise both as external phenomena, in the sense of sound, and figuratively as a disturbance in a signal). This setup is especially necessary in Los Angeles, given its propensity for seismic activity. Lab members did not participate in a citywide earthquake drill in 2008, and, as one student suggested, sitting in the basement laboratory, with its reinforced concrete slab foundation, would be one of the safer places in the city to be during an earthquake. The vibration of the AFM probe due to random external vibrations is less than the length of a single atom. Ironically, in order to listen to the vibrations of cells "in their natural state," a very artificial environment must first be constructed (Pelling et al. 2004: 1150).

As a relation between an organism or some other biological system and its ambient

environment, a milieu is a landscape that influences and in turn is shaped by the organism that occupies it. The notion of milieu fastens organisms to the web of their environment's particularities, drawing attention to an organism's interaction with its environment and with the other organisms in it. In his explication of the conceptual evolution of milieu, Canguilhem writes that it "explains the passage from the notion of fluid as a vehicle to its designation as a medium [*milieu*]. The fluid is the intermediary between two bodies; it is their milieu; and to the extent that it penetrates these bodies, they are situated within it" (1952: 8). He continues: "Circumstances and surroundings still retain a symbolic value, but milieu abandons any evocation other than a position indefinitely denied by exteriority. The now refers to the future, the here refers to its beyond, and so forth always ad infinitum. The milieu is really a pure system of relationships without supports" (ibid: 11).

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

The experience of listening reconstitutes a parallel situation for the listener's bodily

relation to his or her environment. For instance, Julian Henriques describes the experience of listening to dub music as feeling “the pressure of the weight of the air like diving deep underwater... making the experience imminent, immediate, and unmediated” (2003: 452). Sound is a system of relations between at least two bodies. It requires an origin as well as a receiver to sense audible vibrations. While sound has a point of origin, there is no center to the space through which it is transmitted. Bodies are both situated within an acoustic space and are penetrated by it, as it “is a kind of space you are inside as well as outside and it is inside you as well as you being inside it” (ibid: 459). Compare Canguilhem’s biological milieu to Marshall McLuhan’s notion of auditory space:

It is the act of hearing that itself creates “auditory space,” because we hear from every direction at once.... Auditory space, so crucial to architectural problems today, is usually defined as “*a field of simultaneous relations without center or periphery.*” That is, auditory space contains nothing and is contained in nothing. It is quite unvisualizable, and, therefore, to the merely print-oriented man, it is ‘unintelligible’ (1961: 49, emphasis added).

Auditory space implies a listener who defines and demarcates it. That is, by definition auditory space must be a *biological* space, one inhabited by organisms making noise and listening to their own and others’ sounds. Neither immaterial nor purely informatic, sound is a perceptual field requiring topographies, media of transmission, and listening bodies.

A series of milieus is folded into the practice of sonocytology. Each milieu is an array of relations linked to other milieus. There are the milieus of the scientist, who might be ensconced in a vibration-free room (manipulating the probe of an STM or AFM, for example) or sitting in

front of a computer listening to the sounds of yeast flood from speakers into the lab. There is also the milieu of the yeast cell; because the cell cannot be taken out of fluid without dying, it is suspended in a fluid “yeast extract” and flushed through a lattice with 5 μm pores so that a yeast cell is trapped in each pore before being placed in a Petri dish and doused in yet another medium made of pulverized potatoes (Pelling et al. 2004: 1148). After being corralled and pinned by the tip of the AFM probe, the yeast vibrates in its isolated chamber. Beneath the cell wall lies a cytoplasmic milieu inhabited by organelles suspended in cytoplasm and motor proteins that transduce chemical energy from ATP into motor energy in order to build cellular scaffolding and traffic molecules through the cell. The transduction of sound from each of these milieus to the next constructs a soundscape where cellular processes become sensible to biologists, that is, once they have learned how to interpret what they are hearing. Resonances scale the domains and temporalities of previously isolated milieus.²⁸

An acoustic milieu, then, is a milieu shared by two (or more) organisms in relation to each other and to their surroundings. If “the milieu that is proper to man is the world of his perception,” then listening to yeast creates a milieu that he shares with yeast (Canguilhem 1951: 26). It is within this thumping cytoplasmic milieu that we imagine ourselves when listening to cellular noise.

But listening occurs in time and cellular activity is dynamic, so we must also attend to the

²⁸ For Gilles Deleuze and Félix Guattari, “every milieu is coded... but each code is in a perpetual state of transcoding or transduction. Transcoding or transduction is the manner in which one milieu serves as the basis for another, or conversely is established atop another milieu, dissipates in it or is constituted in it.... The milieus pass into one another; they are essentially communicating” (1987: 313).

modes in which sound is transmitted through acoustic milieus. Sound is transduced as it travels through media and mediating machines. Transduction, as engineers use the term, refers to the technically mediated process by which mechanical vibrations are converted into electrical signals. Thompson argues that the technical and material development of transducers in the 1920s and 1930s significantly affected the epistemology of sound: “scientists who used [electroacoustic transducers] began to effect similar transformations between sounds and signals in their minds, developing new ideas about the behavior of sound and the physical objects that produced it” (2002: 96). That is, by turning sound into an electrical signal that could be amplified, manipulated, and transformed, acoustic technology turned sound into information that could be fruitfully studied by scientists and used as data for gathering information about natural phenomena.

Transduction has three definitions, all of which apply to sonocytology. Acoustic transduction is the conversion of a signal, such as a sound wave, from one medium to another. Biological transduction is the transfer of biological information from one organism to another or the translation of a stimulus into an electrical impulse. Technical transduction converts input energy into output energy of a different form by a transducer such as the piezoelectric crystal of an AFM or through a microphone.²⁹

²⁹ A fourth definition of transduction mediates between the technical and the biological, referring to when a machine can predict new outputs based on prior experience of inputs and their resulting outputs, that is, through learning. Henriques suggests that transduction surpasses traditional binary compartmentalizations of the world: “A transducer is a device for achieving the escape velocity to leave the world of either/or and enter the world of either and both” (2003: 469). On the acoustic and biological resonances of transduction for thinking through the ways in which biological objects and spaces are perceived and performed through mediating technologies, see Helmreich 2007, Mackenzie 2002, Myers 2006.

Piezoelectricity defines the reversible conversion of mechanical energy into electricity. Microphones, for instance, transduce mechanical vibrations into electrical signals, while speakers do the reverse. In addition to microphones and speakers, a third kind of transducer is at work; the human sensorium can be understood as a device for converting mechanical energy, light, and chemical stimuli into electrical impulses, as when, for example a post-doc told me the piezoelectric crystal is akin to your nervous system:

Hearing is understood... in terms of a work of transformation. Hearing takes what Serres calls the hard, *le dur*, and converts it into information, *le doux*, or the soft. This exchange is effected by the senses, or by the work of sensation, which, in turning raw stimulus into sensory information, also make sense of the senses, effecting a slight declination, or deflection within the word *sens* itself: sense becomes sense. These transformations are effected in every organism by a series of processes of transformation that Serres is wont to call “black boxes” (Connor 2005: 323-24).

The yeast/AFM/human assemblage that performs sonocytology is a series of vibrations traveling through different media and converted into sound by mediating transducers.³⁰ The kinetic motion of motor proteins becomes a cytoplasmic rumble that vibrates the cell wall, which exerts pressure on a cantilever, causing the piezoelectric crystal to convert the deflection into an electrical output. A graphic trace of its deflection is created, which is then converted using a computer program into an electrical signal sent through a pair of speakers as mechanical wave oscillation, creating a periodic turbulence in the air that vibrates the tympanum, which vibrates the ossicles, which vibrates the fluid of the cochlea, which ultimately triggers hair cells to send electrical signals to nerves that travel to the brain. Each time the signal travels from one neuron

³⁰ On the relation of sound to matter, Deleuze and Guattari claim “it is a question of a highly complex and elaborate material making audible nonsonorous forces” (1987: 95).

to another it must be transduced from electrical to chemical energy while traveling through the intercellular synapse. Thus the acoustic, the technological, and the biological harmonize with one another in a biological soundscape. However, this biological soundscape is in turn culturally transduced, obscuring the technical conditions of its production.

INTERIOR TIME

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

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

Sonocytology captures vibrations caused by intracellular processes unfolding in cytoplasmic milieus. Pressing our ears to opaque cell walls, we hear cellular activity unfold in four dimensions: the busy hum of actin and myosin filaments assembling cellular scaffolding, the whoosh of molecular transport through cytosol, the glub glub of endocytosis and exocytosis. The question remains as to how sound indexes these dynamic interior biological processes and how temporality is fractured by biologists' conceptualizations of the insides of cells.

Sonocytology has been met with reserve and occasional skepticism in the scientific world. Some are unsure whether the sound recorded by the AFM originates within the cells and

have raised the possibility that the vibrations could be due to external factors, such as Brownian motion or the unintentional movement of the AFM probe. However, Gimzewski and Pelling are certain that what they are hearing is the sound of cellular metabolism and the movement of motor proteins, positing that their “experiments reveal a new aspect of yeast cell biology — the *dynamic nanomechanical activity* of the cell wall” (Pelling et al. 2004: 1150, emphasis added). The fact that the frequency of cellular sounds depends upon the temperature and metabolism of the yeast strongly supports their claim.

When, as I quoted earlier, Gimzewski describes AFM as akin to “using your finger to feel a pulse,” his comparison of cellular movement to a beating heart is not accidental; the beating heart stands as an icon of life and motion (Kuriyama 1999). Mediate auscultation, tissue culture, cinematography, and AFM have listened to, isolated, visualized, or probed hearts in an attempt to get closer to the locus of organismic vitality.

One of the first tissues to be kept alive outside of an animal body was a culture of chicken heart cells. Heart cells were chosen “from all the possible organs and tissues of the body, to demonstrate ‘permanent life’ and rejuvenation by culture with a tissue that would manifest life most obviously: the beating heart” (Landecker 2007: 97). Heart cells that continued to beat in culture constituted the most publicly convincing demonstration of artificially sustained life in part because both scientists and laypeople could associate beating hearts with the lively rhythm of their own bodies. “The combination of this natural animate function that every reader could feel thumping away within themselves and the familiar, everyday inanimate object of the glass

jar... resulted in the distinctly uncanny image of life continuing severed from the body and contained in glass” (ibid).

Scientists marveled as heart cells continued to beat autonomously outside of the animal, as if the rhythmic movement of the cells made them more alive than stationary cells. Half a century earlier, Étienne-Jules Marey, who invented techniques for representing physiological mechanics and animal locomotion, developed instruments like the cardiograph and the sphygmograph to measure the pulse. In one experiment he inserted air-filled ampules into a horse’s beating heart and recorded its contractions using a kymograph (Cartwright 1995: 24-6). In one of the first uses of the cinematograph for the study of animal physiology, Ludwig Braun filmed the contractions of a dog’s heart in 1898 (ibid: 20).

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

“Though there is no body here, no actual organ, rhythmic waves course through the cell community. It’s an eerie sight, as if the culture were straining toward organismic identity. This phenomenon has inspired Right-to-Lifers to declare that an 18-day-old fetus has a heart and is, hence, a fully charged human: I beat, therefore I am” (2003: 29).

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

The “vibrating world,” of which sound is but a small, biologically mediated, fraction likewise reveals interior processes, making the interior time accessible, immediate, and mediated outside of the cell (Sterne 2003: 11). While scientists cannot examine cellular activity outside of the cytoplasmic milieu, the cellular interior can be sonically projected into an external acoustic space. Sonocytology, like tissue culture, turns the body inside out in order to render dynamic interior processes accessible.

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

Sound has been used in science to explore and gain direct experience of inaccessible places: to sound the depth of an ocean, the inside of a body, and the furthest reaches of space.³¹ Acoustic technology is also used to connect with absent loved ones, as when telephone wires and satellites transmit disembodied voices, or with people on the margins of life, as in the use of early sound recording to embalm the voices of the dying and the more recent use of ultrasound in obstetrics (Kittler 1999, Ronell 1989). To say that a cell is speaking is to project cultural notions of what it means to be human, to be subjective and have agency, and even for something to be meaningful, into a cellular milieu. Perhaps sonocytology is a mode of imperialism, seizing a cellular colony and asking that its epistemology resonate with our own. This possibility reminds us of the limits of scientific representations: to listen to a cell is always to speak for it.

³¹ In space, the further away a sound originates the older it is. Cosmologists recently analyzed sound waves originating in the early universe to extrapolate the age and structure of the universe. See C. L. Bennett et al. 2003.

If sonocytologists use sound and tactility to collapse macro- and nanoscales, projecting listening bodies into cellular landscapes, the sensorium and its technical mediations also serves as a relay that broadcasts across and between biological scales for molecular gastronomers. These practitioners work with taste to magnify biochemical processes and transformations, using molecules to account for and rethink taste as both embodied sensation and learned discernment. Shifting from the sonic and palpative to the gustatory, it is to this community of allied chemists and chefs that I turn in the following chapter.

Chapter 5: Screaming Yeast

Chapter 6. Molecular Gastronomy: From the Life Sciences to the “Science of Everyday Life”

In a Boston University workshop on science and cooking, I listened to Shirley Corriher, a biochemist and food writer best known for her guest appearances on the Food Network television show, “Good Eats,” explain why she thinks home cooks might prepare better food if they have a grasp of the physical and chemical transformations that take place during cooking. As an example of this “scientific understanding,” she related in a honeyed Georgian drawl how to cook green beans so that they turn a vibrant green rather than a “yucky army drab” color. As she spoke, she leaned forward in her chair, lifting her arms over her ample frame to manically gesture and pantomime biochemical theatrics:

You’ve got a happy little green bean. It’s taking in oxygen, just like we do, using it to burn up big compounds, and it’s giving up carbon dioxide. And you drop it in boiling salted water and *eeeeeeeeee!* Its little protein cell wall coagulates and shrinks and it starts leaking like crazy and the glue between the cells has pectic substances, they call it, and it’s actually hemicelluloses and all sorts of big mess. And anyhow, it changes the plain old pectin, which is water-soluble, so the glue between the cells dissolves and the cells fall apart. I mean, it is just mass death and destruction! The poor cells are leaking and falling apart! You know, it’s no wonder fruits or vegetables get soft when you cook them. So anyhow, but there’s all this acid coming out of those cells. So that’s where the acid is coming from. So the cooking time is going to be vital.¹

¹ Corriher, Shirley, and Harold McGee. “Welcome Back, Shirley Corriher and Harold McGee.” Public workshop, Boston University, Boston MA, April 26, 2009.

The audience, an unlikely jumble of local chefs, restaurateurs, bakers, and MIT and Harvard graduate students, scribbled frantically into notebooks as Corriher talked. After a career as a research biochemist at Vanderbilt University Medical School, Corriher opened a boy's boarding school in Atlanta with her then-husband. Having been a troublemaker during her high school home economics classes, Corriher found herself unprepared to cook for 140 boys and began taking cooking classes. Using her knowledge of biochemistry to explain the culinary catastrophes that inevitably occurred during these classes, Corriher earned a name for herself and embarked on a successful career teaching food science and consulting for chefs.² Corriher finished her recipe by telling her audience that as long as you cook the green beans for less than ten minutes, they will stay bright green. She laughed as she recounted how she once explained "mass [cell] death and destruction" to Julia Child over the phone. Switching between her own voice and a dead-on Julia Child treble, she reenacted their conversation, in which an imaginative understanding of hemicellulose and protein coagulation was of vital importance to Child's recipe for creamed spinach.

Whereas in the Gimzewski lab (Chapter 5), cellular "screaming" is an indexical representation of molecular pumps expelling alcohol from the cell wall, Corriher's high-pitched "eeeeeeee!" affectively conveys the cellular trauma of dinnertime, calling upon our shared cellularity ("just like we do") in order to map molecular events onto the bodily experiences of cooking and eating green vegetables. Corriher's cellular ventriloquism cautioned her audience not to overcook their vegetables, but also to think across scales, and to attend to how their own

² Corriher's first cookbook, *Cookwise*, received a prestigious James Beard Award.

experiences as cooks and eaters are entangled with both biochemical and cellular transformations, on one hand, and broader gastronomical considerations, such as classical French techniques for cooking green vegetables, on the other.

How are “culture” and “nature” unpacked, reformulated, and remade in reference to science in contemporary movements that join scientific practice to craft sensibilities? This chapter addresses these questions by exploring a food movement called “molecular gastronomy,” which practitioners — physical chemists and biochemists who study food, and chefs who apply their results — broadly define as the application of the natural sciences and laboratory apparatuses to furthering the cooking and culinary arts. During my fieldwork in 2009, molecular gastronomy comprised a small network of chemists who devote all or part of their time to studying food preparation and degustation, and dozens of “molecular cooking” restaurants, mostly in the U.S. and Western Europe, which use laboratory techniques such as vacuum distillation and centrifugation, and chemical compounds such as transglutaminase, methylcellulose, and xanthan gum, to concoct new dishes.

In contradistinction to other contemporary research fields in which science and food intersect, such as food science and nutrition, as well as the Fordist and American futurist “modernization of food” in the early decades of the twentieth century (Belasco and Scranton, ed. 2002, Fitzgerald 2003, Page and Walker 1991, Ritzer 2004, Stoll 1988), molecular gastronomers emphasize that the aim of this interchange is not “eating as resource extraction” (Belasco 2006),

but ultimately taste and pleasure.³ It is in this spirit that Harold McGee, science writer and author of *On Food and Cooking*, defines molecular gastronomy as “the scientific study of deliciousness” (1984).⁴ Other currently ascendant food movements — such as Slow Food, locavore, fair trade, and organic trends, not to mention the “caveman diet” — are renovating the way people eat by referencing nostalgic agrarian pasts, local heritages, and ethical or political appetites, which are often posed as reacting to incursions of technoscience into foodways (Heller 2007, Hess 2004, Lyon 2006). In contrast, molecular gastronomy inverts the valuation of “authenticity” over technoscience while placing a premium on taste by ushering in a future-oriented and scientifically-inflected approach to cooking and eating.

Science studies scholars have said little about the role of taste in scientific inquiry. In her account of the revolutionary “new chemistry” in eighteenth century France, Lissa Roberts argues that a fourth technology, which she calls “sensuous technology,” be added to Shapin and Schaffer’s enumeration of material, literary, and social technologies that establish the veracity of experimental results (1985). While sensuous technology is often elided from literary and social portrayals of experimental practice and, Roberts argues, was subordinate to measurement devices and instruments under the regime of “new chemistry,” she encourages historians to attend to how

³ As Warren Belasco says of the culinary modernism he identifies in multiple moments from Victorian fairs to the present,

The modernist future is one of radical discontinuities, of unprecedented needs, drives, and breakthroughs. It celebrates purity, shortcuts, simplification, automation, and mass production while dismissing soil, sweat, labor, craftsmanship, and ornament. Its favorite forms are tubes, beakers, buttons, domes, dials, and tunnels — the tools of engineering.... The modernist declaration of independence from tradition is quite volatile, as it unleashes forces that both support and subvert the growth of consumer capitalism (2006: 166).

The difference is that molecular gastronomers do not dispense with taste — this is not meal-in-a-pill modernism. Rather, they mobilize technoscience in the interest of taste.

⁴ Peter Barham, a molecular gastronomer at the University of Bristol, recently proposed that molecular gastronomy might “give some quantitative measure of just how delicious a particular dish will be to a particular individual” (2010: 2361).

chemists have trained their senses in order to “employ their bodies as sensuous instruments” that can “guide [them] through the richly heterogeneous world of nature” (1995: 510-11).⁵ How might such sensuous technologies also impinge on how molecular gastronomers remake taste as “molecular”? One way to begin answering this question is to pay attention to how *taste* gets remade in experimental and culinary practice, not to mention when wealthy urban Euro-Americans consume the products of molecular gastronomy.

If previous chapters have traced how biology is being remade in the contemporary moment, this chapter will explore what a remade biology makes: how might crafted biologies reshape other domains of action? In previous cases, I found that crafty and constructive tactics are being ported into domains of scientific expertise. Each of the fields I so far have described deviate in at least one dimension from “typical” life science: synthetic biology imports engineering principles, DIY biology undermines professional legitimacy and institutional spaces, the HCCR is executed in an abiotic medium, sonocytology overturns the visualism of microscopy. While biohackers port biological objects and practices outside of the lab, they do so in the interest of de-institutionalizing (or undisciplining) science; molecular gastronomers instead aim to formalize and discipline cooking. Molecular gastronomy shows what happens when biochemical tools and techniques leave biology altogether and circulate in non-scientific locales. In this sense, it may be thought of as a test case for examining how constructive biologies remake those senses I have claimed are implicated in the fashioning of new biological things. Previous chapters have tracked how biological things are made, remade, and understood via craft

⁵ Though her argument is deliberately not keyed to taste or olfaction (“their work is also not, in a crucial way, based on a sense of smell or taste”), Knorr-Cetina makes a similar argument, claiming that the molecular biologist’s “sensory body,” “acting body,” and “experienced body” are all integrated into manual experimental work (1999: 95).

practice; the twist here is that molecular gastronomy ports scientific principles, techniques, and tools into craft, rather than vice versa.

In what follows, I begin by describing ethnographic research I conducted in the only lab entirely devoted to molecular gastronomy, that of the physical chemist Hervé This at the National Institute for Agronomic Research in Paris. After relating the history of molecular gastronomy, I turn to key aspects of crafted biology as they are manifested in molecular gastronomy. I first discuss how molecular gastronomers describe food as familiar and mundane stuff that renders scientific principles apprehensible. Second, I examine how practitioners call into question *where* scientific work should be done (in the lab? in the restaurant or home kitchen?) and *who* could and should be doing it (chemists? trained chefs? home cooks?). I pay special attention to how narratives of heritage and progress remake French culinary pasts and futures, and address how molecular gastronomers denigrate feminized practical knowledge as “old wives’ tales,” seeking to recast cooking as secondary to laboratory-tested data about cooking. In examining how “old wives’ tales” warrant molecular gastronomy research, I unpack how molecular gastronomers think about “culture” in an anthropological language indebted to French structuralism. If the importation of craft practices into scientific fields is a means of remaking things biotic, the importation of scientific practice into cooking remakes “culture,” or a particular notion of culture, into an object of scientific remediation and recapture. By “modernizing” classic French cuisine, molecular gastronomers re-entrench social kinds like nation, gender, and class. I suggest that molecular gastronomers are molecularizing taste, both the somatic sensation and the cultured discernment (Bourdieu 1984), fostering new imaginations of biochemical forms and events, and

refashioning cultures of cooking and eating as always already after preexisting facts of nature as it is understood by science.

INSIDE A MOLECULAR GASTRONOMY LABORATORY

My home base while conducting fieldwork among molecular gastronomers was the laboratory of Hervé This at the National Institute for Agronomic Research in Paris. Hervé This is the name most closely and popularly associated with molecular gastronomy. The self-proclaimed “father” of molecular gastronomy, in lectures and interviews (and conversation), This is given to identifying himself as a Hungarian Jew (in fact, his family is Alsatian). Defending this statement, he told me that he “[has] the right” to say he is a Hungarian Jew, and that he is “probably Jewish, because we are all probably Jewish.” This’s refusal of cultural determination is a way of remaking his heritage to suit him and remaking “culture” as something that can be tried on, fiddled with, or discarded — a vision of “culture” which, as I will suggest later, is central to the culinary project of molecular gastronomy. Though This does not acknowledge it, his choice to be a Hungarian Jew is not random — in 1992, This asked Nicholas Kurti, a Jewish Hungarian physicist and fellow founder of molecular gastronomy, to adopt him as his “second father.” This’s remade family is formed around scientific networks, and he was fond of reminding me during my time in his lab that I was now “part of the family.” He maintains a listserve of everyone who has ever worked in or been associated with his laboratory, occasionally sending out “family photos” of current lab members (often *stagiers* who work for a few weeks to a few months towards completion of a technician’s degree).

This's lab is located in the basement of AgroParisTech in the Science and Engineering of Food and Bioproducts Department, which is in the Analytical Chemistry research unit. The lab, as This admits, is outdated and poorly appointed, at least compared to his previous laboratory at the Collège de France [Figure 6.1]. It is situated on rue Claude Bernard (named after the French physiologist) at the edge of the *Montagne Sainte-Geneviève*, near a host of other technical institutes, such as the *École Supérieure de Physique et de Chimie Industrielles de la Ville de Paris*, the *Université Pierre et Marie Curie*, and the *Institut Henri Poincaré*. My apartment was located on rue Vauquelin (named after the French chemist who discovered beryllium, as well as several organic compounds, among them pectin, malic acid, and asparagine). This's naming of his invented dishes after scientists — lobster Faraday, sauce Wöhler, eggs Vauquelin (yes, the same one) — made more sense to me after walking the streets of Paris. More than once I found myself lost in the Latin Quarter, knowing only, for example, that I was standing at the intersection of Cuvier and Linné, but for the life of me could not find Buffon. That the French, and the Parisians in particular, venerate their French scholarly culture is apparent, and begins to explain This's celebrity status. The combination of scientific celebrity and the French cult of food has produced the perfect growth medium in which a phenomenon like molecular gastronomy can flourish, a space in which, at the table, patrons can literally consume science in the guise of *haute cuisine*.



Figure 6.1. A workbench in the This lab, National Institute for Agronomic Research, Paris. Photo: Hervé This.

When This invited me into his lab (and “family”), I imagined an army of Gallic grad students, energetically whipping meringues and pipetting hydrocolloids best known from fast food labels (gellan, lecithin, xanthan), like Oompa-Loompas with safety training. The reality was more modest: I met Audrey Tardieu, at the time This’s only graduate student, finishing her dissertation on the transport of sugars in fried onions. This’s lab uses technical methods, such as Nuclear Magnetic Resonance Spectroscopy, Ultraviolet Spectroscopy, and thin layer chromatography to analyze quantitatively the structure and behavior of biological compounds. He and his students have investigated the photosynthetic pigments in green beans, the biochemical composition of carrot stock, and the interfacial tension of *trans*-anethol (an ester) in ethanol emulsions (such as Patis).

Research in This's lab is funded by large industrial food and nutraceutical companies, corporations such as Marie SAS (a French company that makes frozen dinners) and Diana Naturals, a firm that develops natural cosmetics, food products, and supplements with names like "Cranpure" (TM) (for urinary tract health) and "HealSea" (TM), "a brown soluble powder standardized in polyphenol phloroglucinol equivalent," marketed as an atherosclerosis preventative. Tardieu was funded by Big Chocolate — Mars, Incorporated — maker of pet food and confections such as the eponymous Mars Bar. But instant rice and cat food is not what journalists write about when they fawn over or scoff at molecular gastronomy. They instead report on mannered and exorbitant restaurants such as The Fat Duck in England, El Bulli in Spain, Pierre Gagnaire in France, and the recent crop of "Chicago School" eateries such as Alinea and Moto. The connection between these industrial food companies and high-end restaurants is the chemicals — whereas previously food additives and texturants like agar and methylcellulose were only found in fast foods and frozen foods, within the last ten years, molecular gastronomers have imported these chemicals into avant-garde cuisine. When asked about these "new" food additives, Rachel Edwards-Stuart, one of only a handful of people worldwide with a PhD in molecular gastronomy, was quick to remind me that many of the ingredients that are used at the Fat Duck are the same as those used in the food industry for many years, and can be found in many commercially available foods such as pre-prepared apple pies and onion rings. Anthropologists Deborah Heath and Anne Meneley, in theorizing "dynamic interplay[s]" between *techne* and technoscience, draw attention to how "artisanal" foods are "imbricated in global industrial production processes;" here is one case in which technoscience is itself used to legitimate food products and "establish practices of distinction" (2007: 594), even

as fast food and *haute cuisine* are increasingly made out of the same funding sources, research agendas, and ingredients. Fast foods and frozen foods fund scientists whose experimental work drives avant-garde “culinary creativity,” but such work cannot be dissociated from the large-scale institutional interests that enable it (cf. Mukerji 1989). The distinction between good taste and mass taste may evanesce when evaluated at either a molecular or a political-economic scale.

A central agenda in the field is applying principles from biochemistry to understand and manipulate the mechanisms of cooking, such as how proteins coagulate or phospholipids form emulsions. Using this approach, Hervé This has developed a taxonomy of sauce whereby 451 classic French sauces are categorized into 23 types (This 2007b). Employing this taxonomy, This has developed a series of formulae whereby he may predict new sauces that would be appealing based on the rules he has determined govern each type of French sauce — a kind of culinary grammar (or periodic table). The foods of interest to molecular gastronomy, or at least its Parisian hub, are rigorously Gallic, focusing on béarnaise, bavarois, béchamel, and beurre blanc, to the neglect of most other national cuisines. In addition to curating French culinary culture, French molecular gastronomers also feel responsible to a French scientific culture. For example, members of Hervé This’s laboratory reproduced and checked the results of Antoine Laurent de Lavoisier’s experiments on meat stocks (This et al. 2006). As I will discuss later in this chapter, molecular gastronomers’ conceptions of culture are fraught — though they subsume culture according to experimental sciences and “molecularize” taste, they do so while privileging and preserving French *haute cuisine*.

I tracked a number of other domains outside of This's lab in which molecular gastronomers may be found: In Paris and New York, molecular gastronomers offer monthly courses open to the public, covering topics such as the biochemistry of liquid smoke. In France, molecular gastronomy has also gained a foothold in university science curricula, where instructors use cooking classes as practical modules for teaching students about biochemical principles and processes. Intrepid geek-foodies interested in cooking molecular cuisine at home can now choose among a number of companies that market chemical additives to the home cook. And should these home cooks run into trouble while preparing their bacon powder or hot transparent savory mousse, they can consult a growing catalog of books with titles such as *The Epicurean Laboratory* (Seelig 1990) and *What Einstein Told His Cook* (Wolke 2008). The domestication of cooking techniques until recently found only in expensive restaurants suggests a tension between costly technologies and the cultivation of taste.⁶ Restaurants are central to the movement's identity, offering well-heeled patrons an opportunity to indulge in mind-bendingly expensive dishes that offer up one version of science, here construed as reasoned, high-tech, and post-cultural, as an object of consumption [Figure 6.2]. It is in restaurants such as these that taste as discernment is married to a narrative of scientific progressivism.

⁶ Bourdieu diagnosed among French camera hobbyists a similar attitude that “resists the seduction of the technical object as much as it succumbs to it... Affecting a disdain for the refinement of technical objects in the name of the refinement of the technician is the most realistic way of recognizing their inaccessibility without renouncing their sophistication” (1990: 18, quoted in Sterne 2003).



Figure 6.2. Lab equipment and chemical additives in the laboratory of the Fat Duck, Bray.
Photo: Sophia Roosth.

HISTORIES OF MOLECULAR GASTRONOMY

How does someone become a molecular gastronomer? The movement is young enough — and fringe enough — that practitioners narrate how they became enrolled in it, describing either how they stumbled across the movement, by reading a book or learning about it on the Internet, independently invented it, by trying to find a scientific explanation or technical fix to an intractable problem in the kitchen, or “converted” to it from research science because of dissatisfaction with “big” scientific questions they felt were important but nonetheless of little consequence to the stuff of daily experience.

The feeling that science should also address seemingly small, everyday, or quotidian concerns was Harold McGee's impetus to begin writing about the science of cuisine in the 1980s. Having received degrees from CalTech and Yale, McGee decided to launch himself on a career as a science writer, only to discover that "people were writing about these big things — cosmology and medicine and things like that, but no one was writing about the science of *everyday life*, and it seemed to me that the kitchen is the closest thing we have to a laboratory at home" (emphasis added). Other molecular gastronomers narrate similar conversion experiences, in which they realize that science as they know it does not adequately address "everyday life." For example, Rachel Edwards-Stuart did her undergraduate degree in biochemistry at the University of Cambridge. She remembers that in her last year she was sequencing part of a photosynthetic gene of a dinoflagellate that "lives in part of the world that I could never even go to. And I remember thinking, how does this relate to my life? Every day I go into the lab and I set up these experiments. But I couldn't relate to it, you know, especially when I knew I would never get to see the organism that I was working on."⁷ After finishing her degree, she moved to Paris to attend culinary school and work in This's lab (where she investigated whether potato salads should be dressed while the potatoes are hot or cold). She then completed a PhD under the instruction of both food scientist Andy Taylor and chef Heston Blumenthal on the applications of science to restaurant cooking.⁸ However, the claim that molecular gastronomy is the "science of everyday life" becomes increasingly dubious when one eats at a restaurant

⁷ Interview with the author. 07 March 2009.

⁸ Part of her PhD focused on novel applications of methylcellulose, an ingredient used to make structures such as hot gels and edible films.

inspired by its techniques and principles, and in particular when one receives the check.⁹ If this is the science of everyday life, then it is so for only a very affluent few.

Because the movement is so young, practitioners are also quick to bolster and legitimate it by reference to an imagined history of proto-molecular gastronomers. The molecular gastronomers, food scientists, and researchers in allied fields with whom I spoke largely recognized their forebears among those scientists who applied scientific principles to the investigation of the properties of food and the changes it undergoes during cooking. Foremost among these antecedents is Sir Benjamin Thompson, Count Rumford. In his 1794 treatise on the construction of kitchen fireplaces, Rumford wrote,

The advantage that would result from an application of the late brilliant discoveries in philosophical chemistry and other branches of natural philosophy and mechanics to the improvement of the art of cookery are so evident that I cannot help flattering myself that we shall soon see some enlightened and liberal-minded person of the profession to take up the matter in earnest and give it a thoroughly scientific investigation. In what art or science could improvements be made that would more powerfully contribute to increase the comforts and enjoyments of mankind? (Thompson 1802 [1794]: 16).

The International Workshop on Molecular and Physical Gastronomy adopted this quote as a motto when it organized a series of summer workshops at the Ettore Majorana Centre in Erice, Sicily beginning in 1992. As an example of the longstanding relationship between science and cooking, McGee cites Royal Society dinners. In 1680, Denis Papin, fellow of the Royal Society, reused a “digester” for softening bones to quickly cook fish and make rich meat stocks, thus inventing the pressure cooker. Other regularly cited examples are Lavoisier’s mid-eighteenth

⁹ A tasting menu for two at Pierre Gagnaire in Paris costs about €800.

century study of meat stocks, Justus von Liebig's study in 1845 of the effects of searing meat, and Pasteur's study of the oxidation of wine in the 1870s.¹⁰

Few molecular gastronomers cite as forebears the “domestic science” or home economics movements of the late nineteenth and early twentieth century, “offshoot[s] of first-wave feminism” (Sutton 2006: 98) that also aimed to rationalize home cooking. Indeed, on the few occasions that home economics is mentioned, it is disparaged. For example, in the Boston University lecture in which McGee claimed kinship with Rumford and Pasteur, he derided Ellen Swallow Richards, the chemist who founded home economics in the 1880s, for highlighting nutritiousness and safety while trivializing taste as “arbitrary and secondary.”¹¹ McGee claimed that the home economics movement's legacy left, literally, a bad taste on American palates that prejudiced many towards molecular gastronomy. Further, he suggested that Richards's program of rationalized control went too far: a recipe for mayonnaise from the 1920s suggests replacing “highly variable vegetable oils with mineral oil,” a choice, McGee mused, that home economists probably made because “mineral [oil] is much easier to handle in the laboratory” than animal or vegetable oils. Molecular gastronomers' identification with esteemed scientists like Liebig and Lavoisier and distance from the home economics movement is certainly an attempt to present the field as strictly scientific and separate from home cookery (with all the gendering that those two categories convey). The “science of everyday life,” perhaps, but not *everybody's* everyday life.

¹⁰ This's pre-history begins even earlier: he places his own work on a timeline that includes a third-century papyrus on meat fermentation.

¹¹ Feminist historians of science have pointed out that women's knowledge has historically been devalued in the sciences, as craftwork, “sensuous activity” (Bleier 1986), and “gynocentric sciences” (Ginzberg 1987) located in “gardens, kitchens, nurseries, and sick rooms” (Hubbard 1987) cannot be assimilated into the “methodolatry” (Harding 1987) of masculinist scientific enterprises (see also Harding 1986, 1991; Jacobus et al., eds. 1990; Longino 1990; Tuana, ed. 1989).

In so speaking, McGee was also declaring that, contra Ellen Swallow Richards, for molecular gastronomers taste is not arbitrary, but reasoned, and that, rather than being secondary, taste is their primary aim.

Nicholas Kurti, a Hungarian low-temperature physicist, took a circuitous route to molecular gastronomy. He did his doctoral work in Berlin during a period of tremendous energy and excitement for physicists. As a graduate student he thrilled at rubbing shoulders with the likes of Erwin Schrödinger, Max Planck, Albert Einstein, Leo Szilard, and Eugene Wigner. When World War II broke out, Kurti decamped to the Clarendon Laboratory in Oxford, where he began work on low-temperature physics and nuclear cooling experiments, eventually being cited in the Guinness Book of World Records for producing the lowest recorded temperature on Earth. Like many of his colleagues, he soon found himself enmeshed in the war effort, working on the Manhattan Project during World War II. There, he, together with colleague Francis Simon, formulated a method of extracting Uranium-235 from uranium ore. In March 1969, Kurti, by then a professor at Oxford and a Fellow of the Royal Society, came out as a gourmand in a lecture delivered before the Royal Institution. One can hear contrition, even the pangs of conscience, in his call to fellow physicists to use their experimental skills to further good cuisine: “physicists... either alone or in the company of engineers, are in the public mind usually associated with all the nasty and unpleasant things: supersonic bangs, hydrogen bombs, our

transport problems caused by the internal combustion engine” (452). It was high time, by Kurti’s lights, for physicists to “contribute to the joys of life” (ibid).¹²

Kurti could dazzle lecture halls packed with physicists by demonstrating how thermocouples and vacuum pumps could be co-opted for kitchen use to prepare, for example, soufflés and meringues [Figure 6.3]. He drew upon his venerable career in low-temperature



Figure 6.3. Nicholas Kurti performing an experiment, year unknown.
Photo: Hervé This.

¹² It is noteworthy that historians of science have credited the postwar boom in the life sciences with physicists’ disillusionment following the bombings of Hiroshima and Nagasaki — “biophysics, the physics of life, became part of the efforts to redeem the physics which had lead to the deadly weapon” (Chadarevian 2002: 75). It could be said that while some physicists turned to the sciences of life, Kurti turned to the sciences of everyday life.

physics research to engineer a dessert he called the “Frozen Florida,” an inverted Baked Alaska in which ice cream surrounds a center of hot sponge cake and jam. He also championed the use of the microwave, suggesting that rather than using the microwave to reheat traditional dishes based on heat conduction, physicists develop “an entirely new microwave cuisine” tailored to the properties of non-ionizing microwave radiation. Though the microwave is now a ubiquitous kitchen appliance, when he delivered his lecture to the Royal Institution, it was still so much a novelty item in Euro-American kitchens that Kurti felt compelled to dismiss his audience’s fears about the home use of microwave ovens:

The objection may be raised that a mushroom growth of microwave cookers which may well follow the advent of a new microwave cuisine could interfere with scientific research involving sensitive radiofrequency detection devices, e.g. in radio-astronomy.... to the best of my knowledge no case is known of a microwave cooker interfering with scientific experiments (465-6).

The New York Times reported on a lecture Kurti delivered at City College in 1976, “Kurti combined frying pans with Bunsen burners to advance his theory that the kitchen was but another place to enlist science in the service of the arts.”

In 1986, spurred by his conviction that “novel or hitherto little-used techniques, or even new concepts, could be transferred from the laboratory into the domestic kitchen” (1), Kurti solicited other fellows of the Royal Society for contributions to a volume on science and cookery. In the preface to the resulting volume, *But the Crackling is Superb*, Sir George Porter, then President of the Royal Society, commented: “The preparation of food and drink is a science where the amateur may still sometimes prevail over the professional, and the artist over the

scientist” (1988: xvii). Much of the book is devoted to recipes submitted by Royal Society members, such as Nobel Laureate Anthony Hewish’s Foolproof Fudge (“occasions arrive in the life of any physicist when no amount of expertise in his craft can compensate for the lack of elementary skills in the kitchen” [ibid: 240]). The tone of the book is tongue-in-cheek, and one can detect in it a bit of discomfort that respectable scientists were compiling their recipes for porridge or marmalade. One Fellow, who declined to be included in the volume, complained that the book “would damage the reputation of the Society and lay it open to ridicule” (ibid: 2).

In her contribution to the book, titled “Domestic Science,” Naomi Datta, then an emeritus professor of microbial genetics at the University of London, writes in a personal register about her frustrations trying to manage juggling her work as a bacteriologist with her role as a mother of three. As she put it, “Bacteriology is, or was, a discipline related to cooking and gardening. The nutrient media were prepared in the Media Kitchen and inoculated, or sown, with bacteria. Most of the latter, unlike garden plants, grew up overnight in a 37° incubator. The apparatus of a laboratory was quite like that of a domestic kitchen.” Struck by the similarities between her kitchen and her bacteriology lab, she decided to start bringing her work home with her:

After I had cooked supper, and it was eaten and cleared away, and the children unhurriedly put to bed, I came back to the kitchen. There I picked bacterial colonies, inoculated the antibiotic plates and then incubated them in the airing cupboard. At first I used my gas hob as a Bunsen burner to flame my wire loops, but later took to using pre-sterilised wooden tooth-picks, discarding them straight into a pan of boiling water (ibid: 211).

While in his 1969 lecture and later talks and essays, Kurti posited that scientific techniques could move “from the laboratory into the domestic kitchen,” Datta’s essay reminds readers of the opposite — that there has always been a bit of the kitchen in the laboratory, and vice versa. Kurti’s project, in trying to bridge the space between kitchen and laboratory, is predicated on an assumption that an evident practical, technical, and epistemic breach already separated the two spaces — a luxury which Datta could not enjoy in her own “everyday life.” But beyond making a claim as to what counts as the proper place in which to do biological research (Datta does point out that “this sort of home-work may be illegal”), Datta also makes a more striking claim about what counts as doing biology in the first place — her answer being that such work is not circumscribed by the laboratory, but allows for other, more colloquial activities as well.¹³ As Datta concludes her short essay, “When I retired, I thought I might miss my bacteria and the everyday work in the laboratory but, in fact, I do not. I still have my kitchen and also a garden for growing things” (212).¹⁴

When Hervé This met Kurti in 1986, he was working as the deputy editor in chief of *Pour La Science*, the French edition of *Scientific American*. In 1980, This had begun doing experiments on his own, drawing upon his training as a physical chemist to explore the rules governing the dishes he would cook at home for his family. The idea of using scientific methods

¹³ Later in this chapter, I delve further into the entanglements of kitchens and laboratories as spaces of artisanal labor in molecular gastronomy.

¹⁴ Within the last few years, Grant circulating water baths have become *de rigueur* in restaurants that apply molecular gastronomy principles. In 2010, Grant water baths were first marketed to home cooks. Datta’s essay is the earliest reference I have found to bringing this particular piece of laboratory equipment into the home kitchen: “Another link between my kitchen and my laboratory was my Grant bath.... At Christmas, I took my bath home. I had no pan big enough to boil a ham, but the Grant bath was just right.... After the holiday, the smell of boiled bacon persisted, despite all attempts at cleaning” (ibid: 211-212).

systematically to study the principles governing cooking recipes first came to him, he recalls, on March 16, 1980. On that day, he was busy preparing a dinner for several friends, and had decided to bake a cheese soufflé, following a recipe he had recently read in French *Elle* magazine. The recipe called for him to add eggs to the batter two at a time. This instruction struck This as illogical — what, after all, is the difference between adding four egg yolks two at a time and simply throwing all four yolks into the bowl at once? This decided to cut corners, and the soufflé was, he remembers, an abject failure. Undeterred, he made the soufflé a second time, and this time was careful to add each yolk separately. The soufflé turned out perfectly airy and light. His curiosity had officially been piqued: what, he asked, was the physical mechanism explaining this particular culinary principle? This began doing experiments in a laboratory he kept in the attic of his home. When an employee of *Pour La Science* learned about This's home experiments, she introduced him to Kurti.

Hervé This and Nicholas Kurti jointly directed the Erice meetings on Molecular and Physical Gastronomy. Although (for reasons that remain unclear to me) she was not credited as an organizer of the Erice meetings, Elizabeth Thomas, a *Cordon Bleu*-trained cooking instructor and wife of a physics professor at Berkeley, was also a driving force behind them. She and Italian physicist Ugo Valdre devised the idea for the meetings in conversation during another meeting at Erice in 1988. Thomas asked Kurti, as a professional scientist, to organize the workshop, later asking Harold McGee to assist Kurti, who by then was in his eighties. Kurti next enlisted This, with whom he had been in animated conversation for several years. The provisional title of the workshop was “Science and Gastronomy.” The proposal that the

organizers sent to the Centre explained, “The broad aim of the workshop is to ascertain where in the conversion of raw materials (meat, cereals, dairy products etc.) into what we eat (stews, roasts, creams, sauces, bread, cakes etc.) and in which aspect of our enjoyment of food there is a lack of scientific understanding.”¹⁵ Topics discussed at this first weeklong meeting included foodstuffs such as bouillon, roux sauces, emulsions, foams, meringues, mousses, and soufflés, the viscosity of milk and cream, the role of micro-organisms in cheeses, as well as kitchen techniques such as microwave cooking and deep freezing.

As McGee and Corriher recalled in their 2009 lecture at Boston University, the title of the Erice workshops was changed at the request of the Centre director, who wanted a less “frivolous” title, something befitting a scientific center — “at the time molecular biology was becoming prominent” and had “a lot of cache,” so “molecular” was appended to the title in a move McGee refers to as “marketing” and Corriher considers “bullshit.”¹⁶ This dropped “physical” from the conference’s name after Kurti’s death in 1998. McGee has since distanced himself from molecular gastronomy, saying the title makes him “cringe” because “no chef is making molecules, or even if they’re using advanced techniques they’re thinking about ingredients. So it’s a really unfortunate legacy [of the meetings].” Ironic, then, that McGee and Corriher both laughed at the inclusion of “molecular” in the movement’s title just a few minutes after Corriher imaginatively articulated the molecular mechanism of blanching and McGee described the chemical senses in a molecular idiom. The name “molecular gastronomy” might

¹⁵ Personal correspondence, Kurti-Zichichi, 27 February 1991.

¹⁶ Perhaps it is because home economics, like molecular gastronomy, also flaunted and broadcast its scientificity in order to lend an aura of respectability to a domestic art, that molecular gastronomers are wary of claiming home economics as a predecessor.

have been a funding tactic, but it was a persuasive one. I will next turn to how molecular gastronomers use cooking to *scale up* the molecular, rendering biochemical events palpable and manifest at the “macroscopic” level.

SCALING UP THE SUBCELLULAR

In his first talk on science and gastronomy, Kurti lamented, “I think it is a sad reflection on our civilization that while we can and do measure the temperature in the atmosphere of Venus we do not know what goes on inside our soufflés” (1969: 462). This quote alludes to a statement written by nineteenth century French culinary writer Anthelme Brillat-Savarin, one often referred to by molecular gastronomers such as This and McGee, as well as allied chefs such as Ferran Adrià and Heston Blumenthal: “The discovery of a new dish contributes more to the happiness of mankind than the discovery of a star” (2002 [1825]: 3). The comparison of culinary objects to astronomical objects serves, in both quotations, to suggest that the object of scientific inquiry need not be inaccessible; science may fruitfully be brought to bear on more commonplace events and pedestrian concerns. Science may be scaled down from stars to soufflés. The idea that scientific principles are as discernible in the quotidian as in the cosmic is further underscored in McGee’s comment to *The Believer* magazine, in which he says of toast: “Protein has no flavor of its own — sugar’s just sweet on its own — but when you heat them together they generate hundreds and hundreds of compounds that are sweet, sour, salty, bitter, and have aroma. It’s like stellar nucleosynthesis: it’s creating the universe in a star” (2009). In conversations and interactions with molecular gastronomers, I was often struck by how nimbly they could talk



Figure 6.4. Biochemistry students, wearing aprons and lab coats, prepare chocolate mousse in a teaching laboratory.

Photo: Sophia Roosth.

across scales, contracting the cosmic and dilating the molecular such that the two were mutually comprehensible. Cooking, I found, was the practice that mediated multiple orders of magnitude. As This once reminded me, percolation theory accounts for both the formation of macromolecules and the spread of epidemics — but the theory is best demonstrated by brewing coffee. More than just an exercise in learning by doing, cooking is one way molecular gastronomers make biochemistry apprehensible as practical and sensory knowledge.

At a Parisian university distinguished for its science curriculum, Dominique Durand, a molecular biologist who studies ribosomes and works as a sometime vintner, teaches a biochemistry class in which students learn the principles of protein denaturation, reduction-oxidation reactions, and other biochemical processes by cooking.¹⁷ On the afternoon of the first lab module, which I attended in March 2009, undergraduates filed into the teaching laboratory and took their places at their benches, where they found both white lab coats and black aprons. Confused, some chose to wear a lab coat, others an apron. Most of the students, erring on the side of caution, donned both lab coats and aprons [Figure 6.4]. My lab partner and I were tasked with preparing a crème anglais. The aim of the protocol, according to Durand, was to gain a material understanding of molecular bonds — i.e. hydrogen, hydrophobic, ionic, and van der Waals — and to explore the biochemical process by which proteins coagulate and denature. After heating the cream over a Bunsen burner, adding vanilla pods, and whisking sugar into egg yolks, I attempted to add the egg mixture to the cream, whisking all the time, while taking fieldnotes with the other hand. As my eye glanced between fieldnotes and saucepan, I was dismayed to see thick curdles forming on the surface of my sauce. The professor, hawk-eyed, pounced upon my sauce, dipping a wooden spoon into the curdles and holding up the incriminating utensil to show the students that the American had spoiled her crème anglais. The lesson, which the biochemistry professor delivered to her class while glancing disdainfully at me, was that “In cooking, as in biochemistry, it is necessary to attend to your experiment.” My failure, it seems, was double: I was neither a good cook, nor a good biochemist. Lacking what she characterized as a “readiness” — having my tools at hand, anticipating the unexpected, and

¹⁷ “Dominique Durand” is a pseudonym.

being attentive to my experimental object — I had not gained the artisanal proficiency that might serve me in either laboratory or kitchen. She then spooned three samples into Petri dishes for observation under a light microscope: an uncooked mixture, a well-made crème anglais, and my spoiled one, labeling them as such. Directing my attention to the microscope, she explained that students can “*see* denaturation because they can see the formation of aggregates [in the crème]. And these aggregates are proteins that are completely denatured. With microscopes, they can see with the eyes. So they understand the molecular modification of proteins and lipids.” As she spoke, I saw other students who had prepared more successful crèmes and mousses dipping fingers and spoons into their experimental results, anchoring their lesson by tasting the results of their benchwork.¹⁸

While observing her teaching laboratories, I talked to Durand about how she developed the course, and why she uses cooking to teach her students about biology. For Durand, cooking is a way of making biological processes both relevant and perceptible. Biochemistry and cooking are both about the “modification of natural things,” but cooking is a way, she explained, to make a “link between biological systems in our cells and modifications that they [the students] can see” not just “in a microsystem, but in a macrosystem.” The macrosystemic processes observable in her teaching laboratory — the formation of curdles in crème anglais, or of a meringue from an egg white — are, for Durand, a way of making cellular processes tangible. Seeing the degradation of a cooked egg white dosed with sodium borohydride, for example, allows students to “understand how they [proteins] have an active role in the cell... so they

¹⁸ The lab socialized students in both biochemistry and good taste. Note that the protocol called for expensive vanilla pods rather than vanilla extract, which had no bearing on the biochemical reactions students were studying. For an account of how French schoolchildren are trained in French food habits, see Leynse 2006.

understand that when they put a lot of protein with cysteine they can make this [disulfide bond] link and modify the structure of the compounds of our cells.”¹⁹ The students can understand in practice, she claimed, theoretical concepts whose “consequence in nature” are otherwise opaque: “they learn [in lecture] that one amino acid, which is cysteine, can create a disulfide link [bond] between another cysteine of the same protein or between another cysteine of another protein, and this link can make a lot of modifications in the cell. They can’t understand [this].” But “when they cook eggs, they *see* the white parts of the egg. When it’s not cooked, it’s gelatinous, and when it’s cooked it’s a gel, it’s white.” For Durand and her students, cooking is a technique used to scale up cellular events, mapping the “microsystem” onto the “macrosystem,” as she puts it. If sonocytologists render dynamic biological interiors externally intelligible, using sound to turn the biological inside out, molecular gastronomers use cooking as a sort of sensor whereby subvisible processes may be magnified and made manifest. I next turn to how such crafty and experimental sensibilities and practices are occasioned by spaces of labor, both kitchens and laboratories. I pay attention to how molecular gastronomers extend and broaden spaces of scientific work, asking how this might prompt a similar extension of the personae and postures proper to that work.

KITCHENS AND LABORATORIES

Like the other fields of practice examined in Chapters 3 and 4, molecular gastronomers are making an implicit argument about what counts as the proper space of scientific labor. As Harold McGee said about his interest in “the science of everyday life,” “it seemed to me that the

¹⁹ Interview with the author. 23 February 2009.

kitchen is the closest thing we have to a laboratory at home.” Like the DIY biologists who have ported experimental and synthetic biology into their homes (Chapter 3), molecular gastronomy entails a mutual displacement of spaces of experimental and artisanal labor. This’s laboratory at the National Institute for Agronomic Research is outfitted primarily with equipment he brought from his home laboratory. One afternoon, as we walked through the lab, he proudly pointed to his lab equipment — centrifuges, thermocouples, microscopes, and balances — telling me that these instruments came from the laboratory he keeps in his attic, where he completed the research for his doctoral thesis. This has been stockpiling secondhand lab equipment in his home since his childhood, when he would split his pocket money between books and chemicals. As a boy, he learned to blow glass so that he could make his own glassware for chemistry experiments. Much of his scavenged equipment was acquired when Prolabo, a European laboratory supply company, shut down. He received other equipment as payment for lectures.

Like the biohackers in Chapter 3, This has outfitted his laboratory on a shoestring, borrowing, reusing, and hoarding equipment as he comes across it. Other molecular gastronomers have similarly provident and sometimes wily ways of cobbling together their equipment: Dave Arnold, a self-taught chef and machinist, is now the director of culinary technology at the French Culinary Institute in New York. He has made a career of being a magpie, scouring eBay to find cheap rotary evaporators auctioned off by Eli Lilly. He also modifies other equipment, drawn equally from kitchen and laboratory supply companies, to build to order new apparatuses (vacuum fryers, for example) for molecular gastronomy chefs such as Wylie Dufresne. Jeff Potter, a Cambridge, Massachusetts-based molecular gastronomer and

author of *Cooking for Geeks* (2010), travels in the same circles as the Boston-based DIY biologists — when Mackenzie Cowell scavenged a 200-pound centrifuge from a high school science teacher, he lent it to Potter, who set to work suspending single malt whiskeys and liqueurs. Such tactics and strategies call to mind Lévi-Strauss's *bricoleur*, who cobbles together something potent and meaningful from bits and bobs and cultural detritus, someone who speaks and works “through the medium of things” (1966: 21). More significantly, such begging, borrowing, and stealing are ways of destabilizing laboratory spaces (and their accompanying furnitures and attitudes) and dis-locating them in non-scientific locales (in the cases of This, Arnold, and Potter, their homes).²⁰ Studying the “science of everyday life,” it seems, necessitates, materially and practically, an integration of scientific work into one's everyday life.

Historians and anthropologists of science have recently argued that a more expansive and inclusive look at spaces of scientific practice can license a similarly diversified appreciation of ways of scientific knowledge-making (Gooday 2008, Klein 2008). Historian of science Graeme Gooday appeals for “studies of these less formally recognized forms of experimental/practical space,” which will reveal the laboratory to be “*more* ubiquitous than previously suspected — and, by the same token, as by no means always a place apart” (2008: 795). In rethinking the history of early modern experimentation, Ursula Klein points out that the “laboratory,” until at least the nineteenth century, referred to any space of manual labor, of which scientific labor was merely one example: “like modern engineering and twentieth-century technosciences such as

²⁰ One molecular gastronomer who staged at *El Bulli* thinks of the importation of laboratory equipment into the kitchen as a sort of “Deleuzian deterritorialization” in which the “contextual transposition” of scientific equipment into kitchens works “against conventions, dogmas, traditions” to produce “unprecedented” dishes (unpublished manuscript, translation my own).

biotechnology, nanotechnology, or the materials sciences, the early modern laboratory produced not only knowledge, let alone knowledge about an immutable nature, but also artifacts and things (such as material substances)” (2008: 779).

The legacy of this broader meaning of the “laboratory” as any space of manual, artisanal, commercial, or experimental labor remains in the etymology of *laboratoire*.²¹ When I scheduled an appointment with an instructor and events coordinator at the Grégoire-Ferrandi School of Culinary Arts in Paris, he emailed to suggest “a good time to visit the laboratory.” I arrived for our meeting eager to tour the cooking school’s laboratory, only to be ushered into a room buzzing with a dozen teenagers in chefs’ whites, some slashing the tops of a tableful of unbaked baguettes, others conveying fresh bread from the oven with long-handled paddles.²² I should not have been too surprised, though — in the neighborhood bakery where, during my fieldwork, I would buy baguettes, pains aux figues, and canelés, the door behind the cash register was labeled “*laboratoire*.”²³ The convergence of experimentation and manufacture among constructive biologies such as synthetic biology, DIY biology, and sonocytology entails a revival of the laboratory as a space of both experimental and artisanal work, and a consequent extension of that space into more vernacular locales.

²¹ While the sense of *laboratoire* as a space of scientific labor dates from c. 1671, an earlier sense of the word as an artisanal workroom for pharmacists and confectioners dates from 1620 (*Le Grand Robert*, V. 5).

²² Here too, scientific precision warranted artisanal virtuosity. As a sign of hospitality, the *boulangier* teaching the class handed me and my tour guide freshly baked rolls, yeasty and warm from the oven. The guide, sniffing the air, commented appreciatively that what the baker was doing was “alchemy.” The instructor shook his head, saying that what we were smelling was not “alchemy” but “chemistry” — as he explained to us, the way he was trained to bake bread and the way his mother baked bread, was “alchemical,” because she blindly and staunchly followed rules, such as how long to let the dough rise, without understanding why. Now, he said, scientists have tested exactly how long bread must rise — 45 minutes, 50, or 60 — yielding bread with the best possible texture and aroma.

²³ Susan Terrio points out that French chocolatiers must learn the “specialized vocabulary for the workshop (*laboratoire*)” (2000: 152).

How do molecular gastronomers explain what it means to “do science” outside of the laboratory? Interestingly, it has little to do with technical skills or embodied knowledges, and much to do with an exploratory and interested posture. Harold McGee said that being a “scientist” in the kitchen:

Is more a state of mind than any particular knowledge that you bring to the experience. In fact, that state of mind is probably much more important because you could be a chemist and blow it completely because you’re not really looking at it in commonsensical terms. And I think that’s really what science is, this sort of *organized common sense*. And that’s why I say you can do scientific experiments in the kitchen and it’s not going to feel like science because it’s basically... trying a couple of different things and comparing them. That’s really the scientific method right there. And then taking that information and using it to understand the next step.

Kitchen science, in this formulation, is *not* about practice — the kind of bench skills learned through repetition — but about a curiosity that, McGee claims, is translatable into domestic domains.²⁴ This *organized common sense*, as he calls it, is consonant with molecular gastronomy’s image as “the science of everyday life.” Common sense here both democratizes the scientific persona and obscures the enculturation into both cooking and science that renders knowledges so self-evident that they become “common sense.”

OLD WIVES’ TALES

Food, and imaginations of heritage and innovation on which molecular gastronomy is premised, are ways for molecular gastronomers to metabolize “nature” and “culture,” as they imagine

²⁴ Both one of McGee’s books and his *New York Times* column are titled *The Curious Cook*.

culture to be something that may, by means of science, be exceeded or superseded. Culture, for molecular gastronomers, is local, historically static, and dominated by feminine know-how, or, as they call it, “old wives’ tales.”²⁵ Culture is a term they often use interchangeably with “tradition” or “national heritage.” But by reference to an a-cultural or post-cultural scientism, practitioners remake “culture” as universal and continuously emergent, always exceeding itself with the innovative capacity of new technologies — a condition Pierre Boisard has described in his account of Camembert cheese in this way:

Modernity implies permanent change; tradition dedicates itself to repeating the past, yet at the same time it has to adapt to new economic and social conditions. Living traditions do not survive as unchanged remnants of the past. Rather, they are permanent re-creations that clearly refer to the past but are capable of adapting to social transformation (1991: 190).²⁶

I include technoscience among Boisard’s “new economic and social conditions.” In a joint statement issued to *The Observer* in 2006, Harold McGee and three of the world’s most high-profile chefs (Ferran Adria, Thomas Keller, Heston Blumenthal,) elucidated the difference between cooking based on “culture” and cooking based on “science.” As they put it, “In the past, cooks and their dishes were constrained by many factors,” one of which was “the necessary narrow definitions and expectations embodied in local tradition.” Technoscience, they claimed, affords the modern cook the ability to “*choose* from the entire planet’s ingredients, cooking

²⁵ For an account of how tradition and modernity are gendered as feminine and masculine, see Felski 1995, Sutton 1994, Terrio 2000, Wolchik 2000.

²⁶ There is a logical hiccup in molecular gastronomers’ reasoning, as when practitioners would remind me that the whisk is a “medieval” device unchanged over centuries, yet claim in the same conversation that laboratory equipment is no more “high-tech” than the oven was when it was first introduced to the kitchen. In framing “culture” as timeless, technical apparatuses become discontinuities imposed on immutable cultural activity, which, once absorbed by “culture,” cease to be technical or novel.

methods, and traditions, and draw on all of human knowledge” to further the craft of cooking.

The authors defined culinary traditions as “collective, cumulative inventions, a heritage created by hundreds of generations of cooks.” Molecular gastronomy, on this view, can both build on and evacuate culinary tradition, supplementing local knowledges and national cuisines with “new ingredients, techniques, appliances, information, and ideas” imported from science. Their formulation collapses culture onto an ahistorical vision of patrimony, which may be subsumed by the current of “universal” technoscientific equipment and rationales. “Culture” becomes a resource to be cherry-picked, a commodity rather than a verb. At the same time, science is premised as always exterior to “culture.”

The way in which molecular gastronomers pivot and contort notions of culture, seeking both to codify and enshrine French culinary culture and to annex it under regimes of experimental deduction, became clear to me in March 2009, while attending *Art, Science, et Cuisine*, a Parisian molecular gastronomy competition. In the event, high school and college students worked with molecular gastronomers to reinterpret classic French bistro fare such as steak tartare, Boeuf Bourguignon, and mille-feuilles, using laboratory techniques such as vacuum distillation and centrifugation, and chemical compounds such as transglutaminase, methylcellulose, and xanthan gum. Over the course of several hours, my eyes glazed over as I saw every permutation of French cuisine inverted, deconstructed, or converted into a gel or foam. Teenagers beamed with pride as they demonstrated how they sculpted beef with transglutaminase, solidified red wine with agar, and vacuum-distilled demi-glace. While being inducted into a genre of scientific progressivism, students were simultaneously initiated into

French gastronomic heritage (Trubek and Bowen 2008). The event exemplified what Marxist historian Eric Hobsbawm characterizes as the “invention of tradition,” in which what constitutes both tradition and modernity are normatively remade by reference to one another, following narratives of authenticity and innovation, nationalism and progress (1992). In so doing, certain parts of French culinary “culture” are privileged over others. Specifically, the sort of craft knowledges transmitted intergenerationally, which molecular gastronomers disparage as “old wives’ tales,” get left out of the tradition of French cuisine as it is reinvented. As one presenter at the competition put it, “*ne modernisons le mauvais*” — “let us not modernize the bad [aspects of French cuisine].”

Culinary culture, for molecular gastronomers, is organized around relations of scarcity and furthered by contingency — cooking cultures, they indicate, are local, regionally unique, and restricted by which foods are available. As a bulletin for the EU-funded INICON project, which has funded This’s lab and the restaurants El Bulli and the Fat Duck, put it, cooking is “deeply anchored in one country’s culture, and tradition is given a great importance in the art of cooking,” but rigorous scientific testing might yet salvage cooking from the “intuitive,” “dubious or possibl[y] false advice” garnered from “tradition.” New research topics in molecular gastronomy are motivated by what molecular gastronomers consider the illogical and retrograde information that dominates cooking practice (“old wives’ tales.”) Instead of taking “old wives’ tales” as examples of domestic “gynocentric sciences” (Ginzberg 1987) that might inform the scientization of cooking, molecular gastronomers frame science as acultural, and hence view “old wives’ tales” as irrational and fundamentally incompatible with science. Under the scrutiny

of laboratory testing, old wives' tales are either dismissed as such or are verified at a molecular level, at which point they are rechristened culinary formalisms. Using French cookbooks to formalize French cuisine seems even more curious when one considers that French cookbooks were first written to codify and nationalize French culinary culture.²⁷ Indeed, the old wives tales molecular gastronomers harvest from cookbooks — such as the mistaken belief that searing meat seals in its juices — very well could be cookbook authors' abstractions and justifications of home cooks' rules of thumb. Women might have seared meat before braising it, but it is unclear whether they did so to “seal in the juices,” or because that is how their mothers taught them to prepare meat. Molecular gastronomers' scrutiny of old wives' tales test and codify cooking heritages already formalized.²⁸

This's laboratory keeps a list of research questions, most of which are prompted by scouring old French cookbooks looking for old wives' tales (Pedersen et al. 2006; This 2005, 2006, 2007a, 2009; This and Rutledge 2009) and chooses which research to pursue based on which questions would also be of interest to the industrial food companies that fund most of the lab's research.²⁹ Other examples of tested old wives' tales include the claim that adding salt to water helps green vegetables maintain a bright color during blanching and that egg whites form a stabler meringue if whipped in a copper bowl. Molecular gastronomers explicitly gender the

²⁷ Arjun Appadurai similarly argues, using Indian cookbooks as an example, that cookbooks serve to “construct” national cuisines (1988).

²⁸ I thank Brad Weiss for this insight.

²⁹ This says the prevalence of old wives' tales prompted him to begin exploring the biochemical principles behind cooking: “As recently as 2001, an inspector from the French Department of Public Education said, during a public lecture, that her mayonnaise failed when she was menstruating. Such old wives' tales were partly the reason behind the creation of molecular gastronomy” (2006: 1063).

transmission of such ideas, as “old wives’ tales” are either relayed from grandmothers to mothers to daughters or codified in cookbooks of French *cuisine bourgeois*, which were written by and for housewives. As Audrey Tardieu, This’s graduate student, put it: “from the generation of my grandmother and mother, only women were cooking.” Old wives’ tales flourish among home cooks, who say, ““oh, my grandmother says this,”” she paraphrased, while “the grandfather doesn’t say anything. These books were for women.”

In a workshop I attended in Paris, This spoke of his work verifying and refuting old wives’ tales and taxonomizing foodstuffs in an anthropological idiom. As he told his audience, “Lévi-Strauss sought kinship structures, and here we have a corpus of precisions, which are even more concrete. So the question arises as to whether they refer to a type of structure to be determined? Could the structuralist tools introduced a half-century ago be implemented here?” This’s parents were members of the mid-century Parisian intelligentsia, and This warmly recalls many dinners with Lévi-Strauss at his parents’ home.³⁰ In recognition of my role in his lab as an anthropologist, he reread *The Savage Mind*, and often brought it up in conversation. In the same workshop, This also cited Frazer’s *Golden Bough* and Lévy-Bruhl’s *How Natives Think*, comparing old wives’ tales to a sort of magical thinking that could be countered with the application of reason and experiment. I winced at This’s mobilization of outdated ethnological theories to align home cooking, and by extension, women’s work, with “primitive mentality.” His reference to social evolutionism and its critics posits “culture” as an inherited accretion of practices and perceptions waiting to be codified by the scientist — either ethnologist or

³⁰ Lacan, Leroi-Gourhan, and Foucault also visited often. Foucault lived in the flat directly above This’s parents on the ninth floor. However, he and This, then a teenager, did not get along.

molecular gastronomer.

That old wives' tales can be ordered, refuted, and categorized by testing them using the equipment of biochemical analysis — NMR spectroscopy, capillary electrophoresis, fluorescence microscopy, gas chromatography, and the like — suggests that molecular gastronomers seek to remediate “culture” — a craft culture strongly correlated with women's practical knowledges — under regimes of technocratic authority. However, the idea that “culture” can be evacuated from cooking practice is already premised on a belief that cooking is a fundamentally functional activity. This view of cooking and eating denies value to the myriad meanings relayed in food that cannot be gauged by laboratory equipment. I am speaking here of food's ability to structure experience according to “forms of memory that are... heteroglossic, ambivalent, layered, and textured” (Holtzman 2006: 374). The product of cooking is not simply food, but reinforced senses of nostalgia, historicity, and ethnic, national, or familial identities.³¹

Molecular gastronomers, nonetheless, define cooking functionally, as a “controlled transformation of natural matter” or, as McGee put it, “taking these natural materials which have a certain chemical composition and transforming them by the use of energy in the form of heat, mostly.”³² Cooking, in this view, is a mechanical and chemical inevitability — their definitions are just as applicable to biochemistry and organic chemistry as they are to food preparation. In examining what “cooking” means to home cooks, on the other hand, social scientists offer an

³¹ On the connection of food to memory, see especially: Holtzman 2006; Lupton 1994; Seremetakis 1996; Sutton 2001, 2006.

³² Public lecture, Boston University. Boston, MA. April 26, 2009.

altogether different definition. They have found that cooking is a multivalent “everyday practice” encompassing “embodied sensory knowledge,” memory, “practical knowledge,” ‘tradition,’ and social embeddedness,” requiring a trained repertoire of judgment and dexterity (Sutton 2006, see also Short 2006). Further, home cooking is “women’s work” in which “power relations and gender roles are established, acknowledged, and represented” (Short 2006). It is a performance in which cooks express ethnicity, class, heritage, lifestyle, religion, aspiration, and political and ethical commitments (Counihan 2004; Inness 2001a, 2001b; Scholliers 2001; Warde 1997, 2000). The denigration of “old wives’ tales,” as much as it is a refusal of women’s practical knowledges, also denies the cultural and social differences — the values, attitudes, power relations and histories — that are an inextricable part of cooking and eating.

In invoking Lévi-Strauss, This explicitly compares his catalog of “old wives’ tales” to kinship systems, the anthropological category in which the establishment of social relatedness is both made in reference to and is productive of “facts of nature” and “facts of culture” (Strathern 2005, see also Franklin and McKinnon 2001, Franklin and Ragoné 1998). The comparison of old wives’ tales to kinship structures, I think, is not incidental, or at least it is telling. Old wives’ tales, like kinship systems, are to him folk categories that may be rationalized, systematized, universalized. To paraphrase and reframe Lévi-Strauss’s relation of culture to nature, molecular gastronomers do not superimpose nor impose “science” on “culture,” but apply science to culture such that a new order is synthesized. Rather than following the project of structural anthropology to uncover the universal elements of social structures that may be generally applied to all societies, molecular gastronomers instead seek to synthesize a universal, reasoned,

scientized (acultural) cooking schema that operates at once in reference to and, they suggest, beyond culture.

It is in this respect that, despite their work to exceed or succeed culture, molecular gastronomers chase *after culture*, to borrow Stefan Helmreich's coinage. Being after culture, for scientists, means two things. First, researchers recognize "themselves as cultural subjects," admitting their own perspectivalism whilst understanding culture as "driven by a universal cybernetic logic" (2001: 621). Second, they are "pursuing [culture] as an object for their own study and explanation," that is, subsuming culture within the object of their study (ibid).

Molecular gastronomers re-install culture in taste, a cultivated and classed appetite for technoscientific fare. In contrast to other contemporary food movements that seek to rescue "real" food (whether local, organic, or slow) from modernization and globalization, molecular gastronomers ask how technoscience might amplify or advance taste. Many molecular gastronomers told me that their movement seeks to answer the question, "what will we eat tomorrow?" Such a question is always calibrated against what we ate yesterday, and what we are eating (or not eating) today. As Marilyn Strathern suggests of minglings of nature and culture, "futures necessarily belong to the present: they are what we imagine for ourselves now. The present is itself only made visible against a past" (1992a: 5).

MOLECULARIZING TASTE

On the desk of his laboratory office, obscured by piles of papers, tattered cookbooks, two computers, and accumulating demitasse cups, Hervé This keeps a small, unmarked metal bottle.

One afternoon, while we were in conversation, This rummaged around on his desk, uncapped the bottle, and, holding it to his nose, inhaled deeply with his eyes closed. He then handed the bottle to me, and I did the same. I am no wine aficionado, but the contents of the bottle smelled like a good wine. A very, very good wine. I asked him what it was, and he told me it was a 1985 Haut-Brion, his favorite wine. Did you save the dregs of a bottle to keep at your desk, I asked? No, he said. His friend, a chemist at Givaudan, the Swiss flavor and fragrance company, knowing This's favorite wine, synthesized it for him as a Christmas gift. Using gas chromatography-mass spectroscopy (GC-MS), he analyzed the odorant molecules of the wine, then synthesized a solution with the primary odorants found in the sample.³³ Sniffing at the bottle, This idly wondered what GC-MS and other analysis techniques might do to French wine producers — any wine could be dosed with an engineered bouquet of molecules — could this lead to the obsolescence of the heritage of French wine-growing? Bottles such as this one do not just idle on chemists' desks — while visiting the kitchen of *Chez Léna et Mimile*, a molecular gastronomy brasserie in Paris's fifth arrondissement, the owner, Christèle Gendre, grinned as she offered me an unassuming meringue. When I bit into it, clouds of frozen air redolent of Shiraz raced through my sinuses and out my nose. The chef had dipped the meringue in liquid nitrogen and laced it with polyphenols, a class of molecules including tannins, which gives red wine much of its aroma and astringency.

Anthropologist Robert Ulin has written of French wine cooperatives that Bordeaux's social capital derives from a "process of invention that transforms culturally constructed criteria

³³ A bottle of Château Haut-Brion Pessac Léognan 1985 currently retails online for between \$360 and \$600.

of authenticity and quality into ones that appear natural,” thereby “making the ‘invented’ appear as common sense” (1996: 39, 52). What becomes of French culinary heritages and connoisseurships, social criteria already authorized as “natural,” when they may be simulated by the sorts of biochemical legerdemain that mark molecular gastronomy? In conclusion, I suggest that taste gets reformatted, scaled down so that its explanatory substrate resides in a sensorial imagination of the molecular. Anthropologists of science have shown that new technologies like genetic genealogy testing often dress up existing race theories in new clothes — “molecularizing” race (Fullwiley 2007, see also Nelson 2008, TallBear 2007). Molecular gastronomers use taste to reformat regnant understandings of nationalism, heritage, and gendered divisions of labor, broadcasting them in a biochemical idiom — “molecularizing” taste.

What is taste? And how does it relate to Taste, the socially cultivated distinction theorized by sociologists such as Pierre Bourdieu (1984)? Molecular gastronomers and those biologists and physiologists who study chemosensory perception refer to taste and olfaction as the “chemical senses,” a term that has been used since at least the Chemical Revolution (Macquer 1778: 392).³⁴ Taste receptors, they say, identify particular chemicals that are either helpful or harmful to the organism doing the ingesting: salt receptors perceive salt cations (lithium, sodium), sweet receptors identify various sugars, bitter receptors recognize those compounds most likely to be poisonous (alkaloids, among them caffeine and theobromine), sour receptors discern acids, and our taste for umami allows us to detect the presence of amino acids and

³⁴ A third postulated chemical sense, “chemesthesis,” detects chemical irritants — think of the sensation of eating pungent foods such as ginger, mustard, and chilies (Barham et al. 2010: 2318).

nucleotides in foods (e.g., monosodium glutamate, derived from glutamic acid).³⁵ Physiological models of taste as organoleptic sensation are explained in terms of molecules. In his account of the molecularization of life, sociologist Nikolas Rose explains that “molecularization” means thinking about life “at the molecular level, as a set of intelligible vital mechanisms among molecular entities that can be identified, isolated, manipulated, mobilized, recombined, in new practices of intervention, which are no longer constrained by the apparent normativity of a natural vital order” (2007: 5-6). Molecularization grounds intervention. What happens when what is being molecularized is not “life,” but the sense of taste? I suggest that when taste is molecularized, it instrumentalizes “culture,” via taste, as both a resource and an object of remediation.

The synaesthetic properties of taste are inscribed in the word’s etymology. Raymond Williams reminds us that early uses of the term had the sense of “touch” or “feel.” Williams traces the manifold meanings harbored by the word *taste*, identifying a separation of “taste” from “Taste” beginning in the eighteenth century. Taste with a capital T, he claims, has since then become “abstract, capitalized and in such ways regulated” and “separated from active human senses,” of which lowercase *taste* is one. Playing off of the meanings of *capitalize*, he argues that Taste “cannot now be separated from the idea of the consumer” (1976: 314). Williams’s characterization of Taste as consonant with culturally manifested rules and habits of discernment

³⁵ Recent studies of taste have also demonstrated that taste is a fundamentally multimodal sense, drawing heavily on olfaction in order to synthesize flavor, and that our sense of taste is heavily influenced by how our foods look, feel, and sound when we bite into them (recent findings in studies of multimodal sensory perceptions of flavor include: Auvray and Spence 2008, Hollowood et al. 2002, Stevenson et al. 1995, Verhagen 2007, Weel et al. 2002, de Wijk 2008, Zampini and Spence 2010). Chefs working in molecular gastronomy have exploited this fact, providing headphones and soundtracks to amplify their patrons’ dining experiences, as, for example, in Blumenthal’s “Sound of the Sea” dish, designed to resemble, taste, smell — and sound — like the seaside, by virtue of an iPod shuffle that replays the sounds of waves and gulls while diners eat.

has strongly influenced the way social scientists evaluate class-based preferences and pretensions. This impact is most apparent in Pierre Bourdieu's *Distinction*, in which the sociologist argues that:

Taste, a class culture turned into nature, that is, *embodied*, helps to shape the class body. It is an incorporated principle of classification which governs all forms of incorporation, choosing and modifying everything that the body ingests and digests and assimilates, physiologically and psychologically (1984: 190, emphasis in the original).

Hans-Georg Gadamer enrolls taste in asserting philosophical hermeneutics, arguing that taste “strikes a balance between sensory instinct and intellectual freedom,” and joins aesthetics to moral orders. On this model, taste is both an embodied phenomenon and one which occasions a judgmental distance (2004 [1975]: 31). Molecular gastronomers remake t/Taste according to a molecularized — that is, scientized and naturalized — imagination of taste as physiological capacity. If Taste is “class culture,” embodied, then it is unsurprising that ascendant aesthetics of technoscientific progressivism have found their way into high-end cuisine, as science becomes something worthy of consumption by cultivated palates.

After a spate of reports of diners falling ill after eating in molecular gastronomy restaurants, a column in *Le Monde* satirically demanded that molecular gastronomers itemize the ingredients in their dishes in the same way that restaurants devoted to sustainable and local cuisine now often do. As the journalist put it, “After all, chefs are always proud to announce that the live langoustines come from Guilvenec or that the Iberico ham is bellota-bellota. So why not

[listed] on the menu of El Bulli: ‘Olive oil spring with E 953, E 473, E 475?’” (Géné 2009).³⁶

On this view, science, in the guise of thickeners, stabilizers and emulsifiers labeled and ordered according to the Codex Alimentarius international numbering system for food additives, displaces *terroir*, the “taste of place” central to French culinary culture that incorporates regional ecologies with local know-how (Barham 2003, Trubek 2008). Chefs cooking molecular cuisine supersede the characteristic taste of foods from Guilvenec or the Iberian Peninsula with an altogether different sort of taste, one whose place of origin is chemical laboratories such as Dow. Molecular gastronomers may be aiming to evacuate cultural values from cooking, but they reinstall them in the guise of molecularized tokens for social criteria, such that consuming isomalt, sucrose esters of fatty acids, and polyglycerol esters of fatty acids, respectively, becomes an exercise in enculturated distinction.

I opened this chapter by asking: What does a remade biology make? In the case of molecular gastronomy, the importation of scientific principles and techniques into craft practice remakes two things, “taste” and “culture,” which are reconfigured in reference to each other. Molecular gastronomers’ work, as I have suggested, is haunted by the Lévi-Straussian formulation of culture as built upon the ordering of sensory perceptions (tasting, smelling) according to conceptual schemas. And it is this other aspect of “culture” — the ordering of the lived world according to sensations and perceptions — that molecular gastronomers pursue. For example, “Food Pairing,” a project launched by a Belgian bioengineer who analyzes the volatile molecular components of various food items, assumes that foods that share aromatic compounds

³⁶ Translation my own.

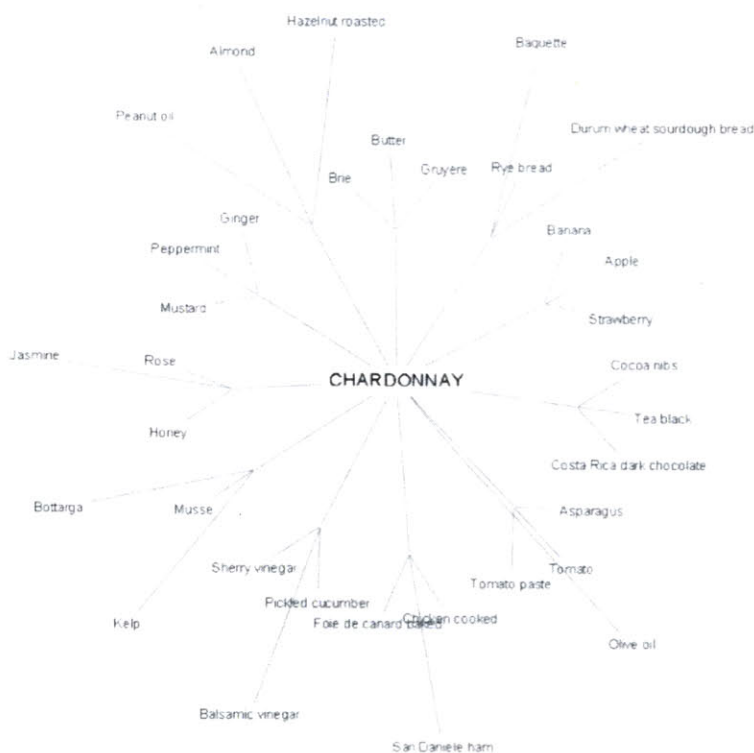


Figure 6.5. Molecular "Food Pairing" Map for Chardonnay.

Source: <http://www.foodpairing.be/>

naturally harmonize with one another.³⁷ I was gratified to learn, while perusing the Food Pairing website, that chocolate and peanut butter pair well because they share the compound dimethyl pyrazine, but unsettled by the implications of the fact that cats and black currants share the odorant methoxymethylbutanethiol.³⁸ Not only does Food Pairing, which currently advises numerous molecular gastronomy chefs, *molecularize* and naturalize taste, it does so according to

³⁷ As a recent review article posed the issue,

Why do some foodstuffs go well with some others but not all? What are the not well-understood chemical and perceptual principles underlying these phenomena? Do 'flavor principles' transcend 'food cultures'? Not such that the very same dishes should be highly appreciated all over the world but such that certain combinations of basic sensory perceptions would be enjoyed universally. Elucidation of these problems would not only be highly interesting from a scientific point of view but could potentially also make a major contribution to more appropriate eating behaviors worldwide (Barham et al. 2010: 2360).

³⁸ <http://www.foodpairing.be>

a particularly Western European perspective on what tastes good: chardonnay shares volatile compounds with brie, but whether, for example, manioc shares heterocyclic compounds with coconut remains unexamined [Figure 6.5]. Projects such as this one refract understandings of food culture, understood as taste, through a molecular logic that systematizes a Lévi-Straussian “aesthetic intuition.” Scientific epistemology here predicts, justifies, and warrants taste. No longer the culmination of densely imbricated relations between foodways, local know-how, regional ecologies, individual memory, and learned discernment, t/Taste is imagined as a side-effect of biochemistry — the three-dimensional conformations and interactions of volatile aromatic compounds manifest not only at the subcellular scale, but rather, like Corriher’s shrieking green bean, now also haunt the embodied experience of cooking and eating, and even the “invented traditions” of French gastronomic cultures.

Chapter 7. Sixth Sense: The Anthropologist as Sensor

FUTURE PERFECT

In conclusion, I return to the claim that animates this work: at the beginning of the twenty-first century, biology has become something known through its manufacture. The world is teeming with biologies we have made, though most of them are not constructive biologies — they may be the sorts of biologies made in the interest of control, synthesis, or design. Or accident. In the weeks during which I finished writing this dissertation, stories about life made and unmade clogged the news headlines: scientists at the J. Craig Venter Institute had built a “synthetic life form” from genetic parts. Meanwhile, an explosion on the Deepwater Horizon oil rig triggered an oil spill that decimated Gulf Coast marine and wetlands ecosystems and imperiled its coral reefs. NASA researchers reported evidence of “cryo-life” on Saturn’s moon Titan. Ten years after Bill Clinton announced that the human genome had been sequenced, the consensus among biologists was that few of the Human Genome Project’s promises had come to fruition (as *The New York Times* put it, geneticists were “back to square one”). Life built, life destroyed, conjectural forms of life, life decoded yet unyieldingly cryptic. Throughout this dissertation, I have argued that the life sciences are undergoing a transformation. The theoretical object of biology is now under construction and reconstruction. “Life” is no longer transparent, and “life itself,” the theoretical and epistemic object of biology, has lost the self-evident clarity that had made it such a compelling theoretical icon in the twentieth century. As I read these dispatches on biologies assembled, devastated, and re-imagined, filtering them through my own

anthropological ears, I got the feeling that biological stories are told in past perfect and future perfect tenses, in which life is always imperiled or nearly here.

Throughout this dissertation, I have recognized constructive and sensory approaches to the biological in a diverse set of fieldsites. In synthetic biology, I discerned how biological systems are being built and rebuilt according to engineering standards, and claimed that the resulting biological systems, in which species boundaries deliquesce in transgenic exchanges, reflect and underwrite how biological materials are freely licensed and exchanged among synthetic biologists and practitioners in allied fields. Tracking such crafted biological things outside of professional laboratories and away from accredited practitioners reveals how hobbyists appropriate standardized biological parts to inaugurate a reflexive mode of biological engagement, through which practitioners construct “biological familiars” — that is, DIY biologists are both the active subjects (biologists) and substantive objects (biology) of their own amateur experiments. For the Hyperbolic Crochet Coral Reef crafters, as for synthetic biologists, their understanding of biology is advanced by the manufacture of biological forms, a practice that I claim produces a process-oriented understanding of biological morphology, as well as an understanding of biotic evolution that borrows from both theoretical biology and folk notions to imagine evolution as itself a mode of open-ended craftwork. Sonocytologists, in listening to cellular vibrations, tune in to constructed cellular milieus as dynamic, material, and affective. Following constructive biologies into other domains of action, I point to how molecular gastronomers use concepts and techniques garnered from biochemistry to remediate French cooking. In so doing, they install gender, nationality, and class in scientific idioms. More and

more, constructive biologists apprehend life through its reconstruction, and make biologies that lend themselves to multi-sensory encounters.

Life scientists and their allies now craft biological things in order to understand the object of biology, making biology *otherwise* in order to explore its limits (whether of standardization, simplification, sensation, morphology, or plasticity). These “constructive” approaches to biology are not limited to the fields included in this dissertation; to a greater or lesser extent, they are part of a groundswell in contemporary biology as the field reconfigures itself in the post-genomic era. In Chapter 2, I used the term “persuasive objects” to express how such remade biologies can impress, impel, and prevail upon life scientists to think differently about the contours of life. Life, according to this logic, is not a closed system, nor does it designate a distinct class of things in the world, but is wobbly and moveable — new biological entities can, through their manifestation, suggest that life has been or may be different than suspected — synthetic biologists, for example, make claims about the origins of life, minimal forms of life, and post-organismic, transgenic, and engineerable biologies. Further, I have suggested that the discipline of biology also is becoming slippery, as biological objects, techniques, tools — even researchers themselves — shuttle across the semi-permeable membrane separating science from non-science and enter new configurations and alliances of participation, interest, access, attribution, and exchange.

Constructive biologies, in refiguring and remaking living substance, also remake biology, both the discipline and its theoretical object. The actors whose practices I have described are

engaged in making new things out of biological substances and constructing new sensescapes with which to perceive biological processes. In so doing, they are making serious arguments as to what “life” is, claims that touch upon how biological substance is organized, disassembled, reassembled, transferred and exchanged, what the difference is between the biologies we encounter in laboratories and in our daily lives, about evolution and ecological interconnections, about how biological things can be perceived, and about how we might interact with them. In fabricating and sensing such biological things, boundaries between natural and artificial, and between observer and observed, are destabilized and renegotiated — the work of crafting and sensing biological things demands that practitioners also engage in a good deal of meaning-making, such that crafting biological things always entails an additional crafting, whereby “life” is also under construction.

I also claim that remaking life entails a further rhetorical transaction, in which practitioners posit that biology *has always been* amenable to their constructive impulses, going so far as to say that biology exhibits those interventions they themselves perform: biology as engineer, as hack, as vibration, as a kind of knitting. In so doing, they destabilize life as an object of investigation. In a post-organismic turn, life is dispersed into technique, as constructive biologists identify their own constructive methods as qualities essential to “life itself.” By assembling, fabricating, and engineering biological things, researchers invest in an experiential and multisensory mode of apprehending the objects they make, and consequently think of life as something partible, tangible, vibratory, olfactory, tastable, and testable.

One reason the senses are now increasingly germane to the life sciences has to do with scale: constructive biologists use sensations as relays that transmit and transduce information across biological scales. For example, sonocytologists use sound to collapse the scale between cellular and listening bodies, projecting listeners into subcellular soundscapes. Molecular gastronomers use taste to map molecular, bodily, and social scales onto one another. Hyperbolic reef crafters, in touching and crocheting hyperbolic marine forms, dilate scales, such that they use accumulated work-hours to gain “a feel for” evolutionary time scales and to point to how individual action impacts ecological and ecosystemic welfares. Biological research within the last two decades increasingly moves across scales, in collaborative, interdisciplinary, and transdisciplinary configurations in which synthetic biologists, systems biologists, genomicists, and ecologists think across scales, grapple with biotic complexity, and traffic between the genetic and the global, the microcosmic and macrocosmic. Sometimes biologists calibrate scales linearly and informatically, via genetic information cataloged in databases, but constructive biologists are also thinking about biological scales using their senses.

TOMORROW’S BIOLOGY?

Two images, each of which was given to me over the course of my fieldwork, serve as fruitful mnemonic devices with which to think through what life becomes when making new biologies is a mode of biological inquiry. Geneart, a German DNA synthesis company that regularly sponsors synthetic biology meetings and competitions, published an advertisement in the program of the Fourth International Meeting on Synthetic Biology. Flipping through the conference’s catalog on the campus of the Hong Kong University of Science and Technology, I

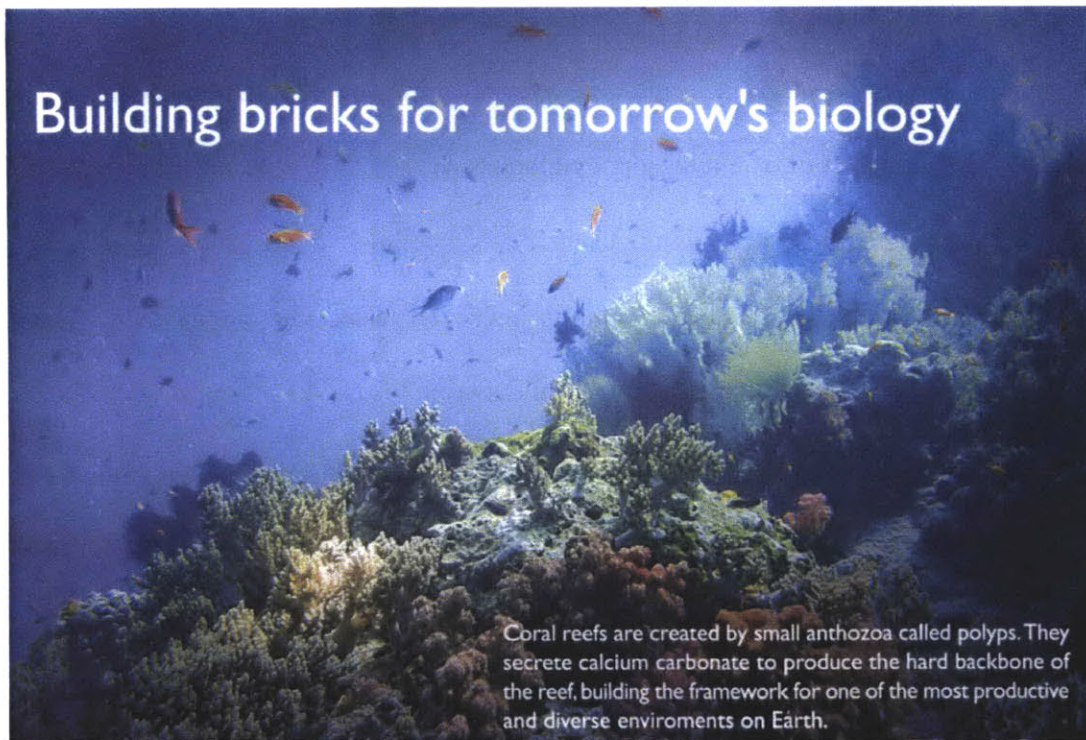


Figure 7.1. Image taken from a Genent advertisement, 2008.

Source: *The Fourth International Meeting on Synthetic Biology Conference Program.*

Figure 7.2. Crochet Coral and Anemone Garden, Sea Slug by Marianne Midelburg.

Photo: Alyssa Gorelick/IFF Archive.

was momentarily confused to find the pelagic photograph in Figure 7.1 in a synthetic biology conference program. My head, stuck in some other time zone, took a few beats to catch up — did not this image belong in one of my other fieldsites? The advertisement shows a color photograph of a coral reef beneath the slogan “Building bricks for tomorrow’s biology.” The reference to bricks alludes to the genetic components that synthetic biologists design and synthesize to be easily composable, BioBricks. The small print on the bottom of the advertisement reads: “Coral reefs are created by small anthozoa called polyps. They secrete calcium carbonate to produce the hard backbone of the reef, building the framework for one of the most productive and diverse environments [sic] on Earth.” The ad does not highlight the imperiled nature of today’s coral reefs, the fact that if recent trends of increased salinization and water temperature remain unchecked, reefs such as the Great Barrier Reef may well not be a part of “tomorrow’s biology.” Instead, we may discern a return to the architectural metaphors that Stefan Helmreich recognizes in nineteenth century British biologists’ figurations of coral reefs in Geneart’s comparison of calcium carbonate depositions to BioBricks, which anticipate and presuppose some sort of bio-architecture — durable, composed, structured — that these bricks, ostensibly uniform and mechanically produced — compose (forthcoming). Further, the advertisement naturalizes the standard BioBrick component by comparing it to polyps’ calcium carbonate depositions, implying that a bottom-up approach to constructing biotic systems is something already innate to biotic formations. Synthetic biologists’ BioBricks, on this view, are only slightly tweaked versions of natural modes of construction.¹

¹ Helmreich also has argued that objects of biocapital are doubly fetishized, “infused with vitality because of the erasure of the labour and regulation that allow them to appear ‘in themselves’... and simultaneously imbued with life because of their origin in living things” (2008b: 464, see also 2007). Geneart’s advertisement also fetishizes BioBricks by re-imagining them as natural and naturally generative things akin to coral polyps, hoping to cash in on life’s “productivity” and “diversity.”

The sorts of fabrications envisioned by Margaret and Christine Wertheim, the twins at the helm of the Hyperbolic Crochet Coral Reef, are altogether different from those of Geneart. Figure 7.2 arrived on my doorstep in March 2007, when The Institute For Figuring mailed postcards to its members publicizing the exhibition of their Reef at the Andy Warhol Museum in Pittsburgh. The photograph of the crocheted Reef, rendered in striking shades of chartreuse and heliotrope, accompanies this text:

The Great Barrier Reef, one of the acknowledged wonders of the natural world, stretches along the coast of Queensland Australia in a riotous profusion of color and form unparalleled on our planet. But global warming and pollutants so threaten this fragile monster, that scientists now believe the reef may be dead in 30 years. In homage to the great one, the Institute For Figuring has undertaken to crochet a handmade reef. This wooly testimony to the disappearing wonders of the marine world duplicates the strange hyperbolic geometry of the oceanic realm.

The contrast between the monumental brickwork of synthetic biology and the colorful fabrications wrought by the Wertheims and their army of women crafters sheds light on the many modes of crafting that constructive biologists undertake. It reveals at least two sorts of engagements with the biological, one unrepentantly future-oriented (“tomorrow’s biology”), and the other engaged in a kind of biological salvage work, in which the unraveling of our ecosystem is paired with a renewed effort to demonstrate how the global biological has always already been knitted together.

Whereas the surface of the crocheted reef curves away from itself exponentially, synthetic biology aims to tame biotic efflorescence into structured and predictable technical systems. And

biohackers, who are aligned with the technical dispositions of synthetic biologists but cast about for non-professional locales in which to perform bioengineering protocols, aim to domesticate synthetic biology as a scientific, albeit household, form of life. While synthetic biologists aim to domesticate biology in terms of its substance, where “domesticate” means to tame and train biological matter to operate akin to inorganic things, both Reef crafters and biohackers also are domesticating biology, by importing biological work into domestic spaces, albeit in very diverse ways and toward diverse ends. I mean “domesticate” here in its primary sense of “to cause to be at home; to naturalize” (OED), because this act of domestication is not meant to tame or train synthetic biology in any meaningful way, but to do the opposite, by setting the protocols and tools of bioengineering loose to proliferate in the wide world outside of the laboratory and the strictures and proprietary regimes of professional academic and industrial bioengineering.

Though the Reef’s hyperbolic configuration is, for its crafters, a *material* instantiation of both biological and mathematical formalisms, the hyperbole of my other fieldsites works in a more rhetorical than geometrical register: each one seeks to render biological substance as itself amenable to practical interventions, as something always about to get away from itself, whether through its standardization and circulation, its deinstitutionalization, its sonification, or its gustatory rationalization and ingestion. Sonocytology is doubly hyperbolic, “exaggerating” and “intensifying” cellular vibrations, both by amplifying their volume and by claiming them to be meaningful *sounds*. Molecular gastronomy hyperbolically promises to project food — and those who eat it — into a post-cultural near-future in which food is no longer freighted with the accretions of local tradition and know-how. Biology, in each of these cases, is in excess,

exceeding itself, or seeking to work *beyond* something — beyond the organism, beyond disciplinary biology, beyond culture, history.

In *On Beyond Living*, Richard Doyle pursues what happened to the “beyond” — the unified hidden force animating “life itself” that Foucault claimed conditioned the field of biology — over the course of the twentieth century. Mid- to late-twentieth century molecular biology, he argues, constructed a “postvital body” for which “the overlooking or disappearance of the body displaces this ‘beyond’ onto an ever denser and ever more complex genetic apparatus” that transparently announces “that is all there is” (1997: 17-18). If, on this view, molecular biology was an act of closure or “the end of narrative” (ibid: 20), the constructive biologies that flourish with the return to biological substance and complexity in the twenty-first century restore narrative to biology, making biological things that tell stories about origins and ends, sometimes erasing pasts, sometimes crafting homages to it, sometimes warning of risky futures, sometimes auguring and promising biologies to come.

If the Hyperbolic Crochet Coral Reef’s manifestation is geometrically hyperbolic, synthetic biology, DIY biology, and molecular gastronomy manifest themselves as rhetorically hyperbolic, given to pronouncements and predictions that anticipate, and even bank on, technologies that may develop, speed up, or be more cheaply available in the not-too-distant future, or on future-oriented imaginations of biological substance. It is worth noting here that those three of my five fieldsites whose movements or disciplinary home bases are well-enough established to be named, have all been renamed, or rebranded: detractors say that synthetic

biology is just a sexier name for bioengineering or biotechnology, that molecular gastronomy is just food science in nicer clothes, and that nanotechnology, of which sonocytology is a technique, is materials and surface science with good PR. Both organisms and scientists can make good use of hyperbole to extract resources from their environments. Mike Fortun writes of the shared valences of scientific “hype” — exaggerated publicizing and future-oriented promising — and “hyperbole:” “what hype is must be speculated on, an operation that thus partakes of the rhetoric of hyperbole itself” (2008: 304, fn 1). Speculative or promissory thinking in the life sciences is by its very nature hyperbolic, and the hyperbolic excess of speculative thinking is knitted to the generativity of biological substance (Franklin and Lock 2003; Helmreich 2008a, 2008b; Thompson 2000). As Kaushik Sunder Rajan puts the matter, “to generate value in the present [is] to make a certain kind of future possible.... Excess, expenditure, exuberance, risk, and gambling can be generative because they can create that which is unanticipated, perhaps even unimagined” (2006: 116). For Geneart, the hyperbolic “excess of space” that coral reefs embody operates as a visual familiar with which to articulate possible biological futures, and concomitant excesses of value, in which the company seeks to stake its claims via a promissory summoning of future biologies. Sunder Rajan points out, paraphrasing Nietzsche, that the future value of biotic things functions by dint of their being “artfully knotted and crocheted” to “antithetical things” (ibid: 118). Such an abductive reasoning, as Stefan Helmreich articulates it, “joins hope to reason, present texts to future contexts, contemporary life forms to scientific forms of life yet to come” (2008a: 172).

RETOOLED METHODS FOR REMADE BIOLOGIES

As I have argued in this dissertation, not only is biological substance and form being remade, but biology, in the early twenty-first century, is being done differently — by different sorts of people, in different sort of places, and for different ends — than those which anthropologists and historians of biology are accustomed to examining. Remade biologies demand remade forms of ethnographic accounting. At a moment in which biologies are made and remade, sensed and made sense of, “participant observation,” with its air of perspectivalism and remove, seems an inadequate term for the work of detecting and discerning the lively, hands-on, apprehensive, volatile, and engaged modalities of work ascendant in the life sciences.

Sensory ethnographer David Howes has called for supplanting participant-observation, with its emphasis on visual perception, with “participant sensation,” a methodology in which the ethnographer must “become a sensor” impacted and impressed by her emplacement in fields of cultural practice (Howes 2006: 121; 2008). He does not elaborate on what being a “sensor” might mean, but, guided by my fieldwork, I advance and specify the notion of the participant-sensor as a model for ethnographic work. A *sensor*, the OED explains, is “a device giving a signal for the detection or measurement of a physical property to which it responds.” The earliest uses of the term supplied by the dictionary date from the Cold War, referring primarily to technologies developed by the U.S. Air Force and NASA to deploy missiles and measure the health of astronauts. The participant-sensor, then, plugs into a patently cybernetic model for registering physiological and environmental conditions, one that mid-century anthropologists used to inform their own practices. It also references the notion of the fieldworker as a carefully

calibrated “instrument.”² By participant-sensor, what I have in mind is a mode of sensorially attentive fieldwork in which the ethnographer is alive to the gaps, stutters, and swerves that mediate and modulate between sense data and sense-making, both on the part of life scientists and the social scientist. Being a participant-sensor means that one’s body and sensorium is entrained and attuned to researchers’ sensory engagements with the biological, filtering their apprehensions through one’s own impressions and perceptions of the social field. It means registering multisensory signals and being moved by them, and cultivating a cognizance of the fact that how the sensor senses and *makes sense of* is always inflected by circumstantial, partial, oblique, and entangled commitments. Participant-sensation, following Haraway’s call for “situated knowledges” that “build meanings and bodies that have a chance for life” (1988: 580) and Karen Barad’s use of “intra-action” to designate how experimental subjects and objects are mutually constitutive (2007), is a way of tuning into the intimate exchanges between researchers and their biology, and maintaining a focus on what biology becomes when it is no longer code, and what biological practice means when experimentation and fabrication intercalate.

Surveying how ethnographic methods have been “retooled” and “renewed” by anthropologists and science studies scholars in recent decades, Michael Fischer contends:

² In conversation with cyberneticians such as Warren McCulloch, Norbert Wiener, and Walter Pitts, anthropologist Gregory Bateson offered a cybernetic model for the human sensorium, arguing that the sensorium functions like an “analogic” calculating machine, in which external changes trigger corresponding internal, observable changes in the calculating machine. Without collapsing this model onto pure physiology (Bateson discounted that the central nervous system was a calculating machine), he did think that:

there is a possibility that the whole moving body may be used as an analogic component. It is probable, for example, that some people empathize the emotions of others by kinesthetic imitation. In this type of thinking, the body would be an experimental analogue, a model, which copies changes in the other person, and the conclusions from such experimental copying would be derived by the more digital central nervous system which receives proprioceptive cues (1951: 171).

We [ethnographers] need perhaps today a more informatics and biological imagination. Both biology and information are lively, ever escaping their temporary restraints and regulators, creating anew. Ethnography today is thus held to a higher standard than ever: it is a matter of opening the simplified accounts, making accountability possible at different granularities, signposting the labyrinths of possible inquiries for their relevance, their points of no return, their conceptual reruns, of reinvigorating civil society and its recursive public spheres (Fischer 2009).

What might a “biological imagination” in ethnography feel like? I agree that as biology “creates anew,” so must ethnography. Yet the “biological imagination” today is not what it was a hundred years ago, or even ten years ago. What emergent “biological imaginations” do constructive biologists now promote, and how might ethnographers heed them to ground and retool their own practice?

As a methodological tool, I take seriously my subjects’ own practices, contexts, and explanations, and seek to draw upon and metabolize constructive biologists’ practices and hypotheses, working with and across them to formulate my own theoretical stances and commitments. I do not mean this approach to be mimetic, imperfectly miming or simulating constructive biologists’ practices, but simply to be resonant with, impacted by, or rhyming with their own inquisitions. Constructive biologists themselves offer one model of how anthropology of the life sciences might keep pace with the constructive turn in biology. Some of the tactics and sensibilities my interlocutors use to fabricate and apprehend biology guide my own participant-sensing of the life sciences. In each of my fields, constructive biologists are taking new tacks with which to make sense of biologies, making new biological things and bringing their entire sensorium to bear on their investigative and constructive work. In what follows, I

take a cue from two of my fieldsites — synthetic biology and sonocytology — to reflect on how my subjects' practices have informed my own.

From synthetic biologists and DIY biologists, I learned that understanding the biological can be advanced by making new biologies. Such a disposition is also newly relevant to anthropologists who, in entering the field, not only observe cultural activity, but also, by dint of their very presence in the field, are always making and partaking in social encounters, conversations, relationships, and work. George Marcus has forwarded the para-site as an ethnographic method that gathers participants from an ethnographer's multiple fieldsites to bring them into a conversation somewhere between an academic workshop and fieldwork. He explains that "the para-site always involves a material dimension, a kind of labor, or a *making of things out of the way they are supposedly or otherwise given*" (2000: 7, emphasis added).³ Ethnography also entails a "making of things" otherwise, such that fieldworkers forward-engineer the interactions they wish to account *for* and write an account *of*. Like synthetic biologists, ethnographers increasingly make social forms and relations as a mode of inquiry, and are increasingly attendant to the consequences of such constructive ethnographic work. While my own work was not strictly para-sitic, this dissertation is crafted from a series of fieldsites whose members do not recognize one another as kin — I am the common denominator who recognizes

³ The para-site also references Michel Serres's *parasite*, a conceptual figure with which the philosopher posits that communication feeds upon a certain amount of static, or noise, in its meaning-making (2007). Most ethnographers would no doubt nod vigorously at this sentiment, as ethnographers often must parse signal and noise (and make sense from static), as well as, following Serres's other referent for the parasite, learn how to be the uninvited guest at the table.

them as falling under the rubric of “constructive biology.” As such, this dissertation is somewhat of an assembled system in which diverse forms of life are brought into close association. Unlike synthetic biologists, I do hope that my own engineered system has emergent (analytic, heuristic, interpretive) properties that I could not assay in advance.

In my opening chapter, I identified several features of craft practice that I consider newly relevant to how researchers make biological things, among them: it requires a cultivation of the sensorium obtained through practice, crafting biological things is coupled with self-making, and making biological things is a way of generating biological knowledge. These features are certainly not unique to biology, nor are these aspects of craft limited to traditional kinds of artisanship. Tim Ingold argues that anthropology is also akin to craft practice in that “both the practitioner’s knowledge *of* things, and what he does *to* them, are grounded in intensive, respectful and intimate relations *with* the tools and materials of his trade. Indeed, anthropologists have long liked to see themselves as craftsmen among social scientists, priding themselves on the quality of their handiwork” (2008: 84). In outlining the qualities of anthropology that are consonant with craft practice, Ingold quotes C. Wright Mills’s *The Sociological Imagination* (1959), to claim that in the craft of anthropology, “there is no division between method and theory,” “there is no division, in practice, between work and life,” and that, as Mills writes, the social scientist “forms his own self as he works towards the perfection of his craft” (1959: 216, all quoted in Ingold 2008: 85). Making as a form of knowing, and crafting things as an avenue to constructing selfhood: these are aspects of artisanship shared by constructive biologists and, it seems, anthropologists. In what follows, I will use the practices of sonocytologists to explore

how anthropology (and the method of participant sensation for which I here make a case) might also take sensory cultivation as a model for anthropological work.

In James Gimzewski's lab at UCLA, many students were preoccupied with the comparative phenomenologies of the lab's research tools, scanning tunneling microscopy and atomic force microscopy: scanning tunneling microscopes hover above subvisible surfaces, registering atomic-level attractive and repulsive forces, transducing into a topography the push and pull a substrate exerts on a probe. Atomic force microscopes, on the other hand, come much closer to a surface, "touching" it or "feeling it" to sense material qualities such as surface tensegrity, firmness, and vibratory frequencies. Thinking out loud about their machines, graduate students would ask whether the probe was *really* touching a surface, what counted as "contact" when a probe was positioned in "contact mode," and whether the objects they were seeing on the screen were real or artifactual. As a fieldworker, I was concerned with similar questions about contact, data, interaction, attraction and repulsion. Lab members called both AFMs and STMs "transducers," and, as one postdoc explained to me in a sensory analogy, if the probe is like your finger, then the piezoelectric crystal is your nervous system: the transducer, he told me, is "a way to know what you're feeling." When Gimzewski described his experiments in cellular acoustics to me, he emphasized that many of his colleagues were uncomfortable with what he termed the "intimacy" he achieved with his scanning tunneling and atomic force microscopes, because they prefer to "observe at a distance" what he prefers to "listen to" and "feel." The same could be said for the ethnographic project, which requires a resonating of

ethnographer with interlocutor that cannot be neatly summed up as “participant observation,” even when the accent is on *participant*.

Prompted by his own sonic ethnographic excursions, Stefan Helmreich submits “transductive ethnography” as a theoretical and methodological approach. By “transductive ethnography,” he means:

inquiry motivated not by the visual rhetoric of self-examination and self-correcting perspectivalism, but by auditorily inspired, lateral attention to the modulating relations that produce insides and outsides, subjects and objects, sensation and sense data, that produce the very idea of presence itself. Rather than seeing from a point of view, then, we might tune in to surroundings, to circumstances that allows resonance, reverberation, echo — senses of presence and distance, at scales ranging from the individual to the collective (2008a: 230).

Hearing students in Gimzewski’s lab grapple with sensory analogies for their own experimental apparatuses and biological objects tuned me in to the ways in which my own work resonated with theirs: I might approach my subjects, but any sense of contact I might feel was a secondary inference — an artifact of — forces operating across gaps and distances, by which subject and sensor exert influences on one another. Helping graduate students build their own atomic force and scanning tunneling microscopes also brought to my attention that transducers are built, tailor-made to answer particular experimental questions. The anthropologist-as-transducer must also adapt and attune to particular subjects, questions, and locales. More than ethnography as participant-observation, my own experience was nearer to participant-feeling-around-in-the-dark,

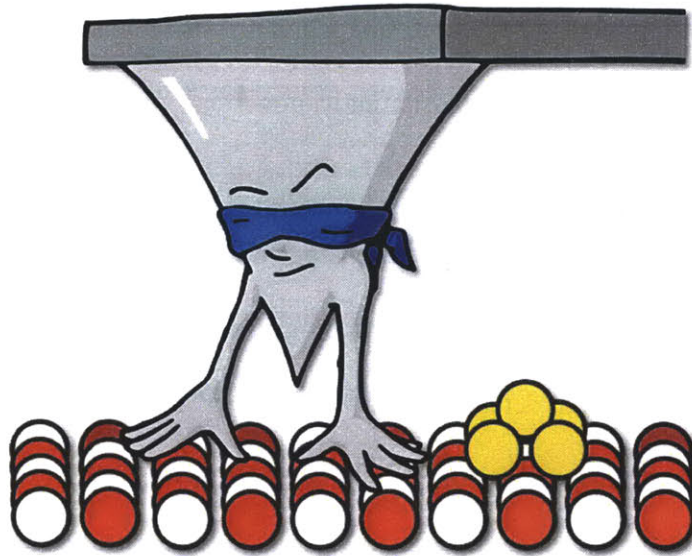


Figure 7.3. Illustration of how a scanning probe microscope “feels” a nanoscopic surface. Source: The homepage of the Department of Applied Physics at the Helsinki University of Technology.

a sentiment shared by the sonocytologists, who described to me both the experience of learning how to do laboratory work and the mechanism by which probes touch cellular surfaces as blindly “feeling around in the dark” [Figure 7.3].

As I argued in Chapter 5, sonocytologists, in recording cellular noises and comparing them to speaking, singing, or screaming, represent cells as subjects capable of speaking to their own conditions. In so doing, they call forth a cellular subjectivity and simultaneously speak for cells. As a model for ethnography, sonocytologists’ practice reminds me that subjects and objects materialize in their sensing, and in the material conditions in which sense data are gathered (whether ethnographically or via scanning probes), and the process of transducing signal into sound is never a high-fidelity recording. Cultural forms and praxes, in the act of

being recorded and interpreted , also get reformatted. I am also reminded of the interpretive dangers of speaking for others, as I do, hesitatingly, now.

Biologists and their allies believe that sensing and crafting new biological things underwrites understandings of the biotic; anthropologists may well be manufacturing new cultural things in the service of “detecting” and “responding” to social practice. The ethnographic substrate shimmers into relief as the participant-sensor edges towards it — the fields we choose, the cultures we circumscribe, the practices we identify — they precede us, yet they are made sense of within the ethnographic encounter. This has consequences for how projects are imagined and designed. For this study, I chose a series of very different fieldsites in order to diagnose a moment in the life sciences. Yet these fields do not belong to any clear “discipline” or shared “culture;” they overlap in places, but members of each do not recognize one another as kin. The common denominator — that cultural thing I term “constructive biology” — is an effect and a consequence of my own participant-sensation, of my work sensing and transducing life scientists’ practices. In scanning probe microscopy, and experimental science in general, the word for something emergent or apparent in a sample that is a result of the investigative apparatus is an *artifact*. Something made by human hands; a crafted object.

CODA

In this study I have claimed that as “life,” at the tail of the twentieth century and the twenty-first’s head, became an increasingly unstable concept, its investigation became progressively amenable to constructive and multi-sensory approaches. Life, to paraphrase synthetic biologists,

became “what we make it.” More than pointing to an absence of any coherent referent for “life,” this trend demonstrates that not only is “life” something richly constructed, but so is biological substance; so is biological practice. Technical and epistemic knowledge were not previously separate entities, as the last three decades of histories of technology have demonstrated.

However, in the fields I have here detailed, life scientists and their allies are building biotic things in order to understand the things that they themselves are making. So making here is not a means to an end, but operates in a dialectical relationship with the epistemic work of investigation, examination, and analysis. As “life itself” deliquesces and recrystallizes, reforms and deforms, in the hands of constructive biologists, the relations between making and knowing are also reconfigured, with serious consequences for the regnant stories we tell about nature and artifice, analysis and synthesis. To keep pace, we must be attuned to them.

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