



# Biobricks and Crocheted Coral: Dispatches from the Life Sciences in the Age of Fabrication

## Citation

Roosth, Sophia. 2013. Biobricks and Crocheted Coral: Dispatches from the Life Sciences in the Age of Fabrication. *Science in Context* 26, no. 1: 153–171.

## Published Version

doi:10.1017/S0269889712000324

## Permanent link

<http://nrs.harvard.edu/urn-3:HUL.InstRepos:12563736>

## Terms of Use

This article was downloaded from Harvard University's DASH repository, and is made available under the terms and conditions applicable to Other Posted Material, as set forth at <http://nrs.harvard.edu/urn-3:HUL.InstRepos:dash.current.terms-of-use#LAA>

## Share Your Story

The Harvard community has made this article openly available.  
Please share how this access benefits you. [Submit a story](#).

[Accessibility](#)

## Science in Context

<http://journals.cambridge.org/SIC>

Additional services for **Science in Context**:

Email alerts: [Click here](#)

Subscriptions: [Click here](#)

Commercial reprints: [Click here](#)

Terms of use : [Click here](#)



---

## Biobricks and Crocheted Coral: Dispatches from the Life Sciences in the Age of Fabrication

Sophia Roosth

Science in Context / Volume 26 / Issue 01 / March 2013, pp 153 - 171

DOI: 10.1017/S0269889712000324, Published online: 11 February 2013

**Link to this article:** [http://journals.cambridge.org/abstract\\_S0269889712000324](http://journals.cambridge.org/abstract_S0269889712000324)

### How to cite this article:

Sophia Roosth (2013). Biobricks and Crocheted Coral: Dispatches from the Life Sciences in the Age of Fabrication. Science in Context, 26, pp 153-171 doi:10.1017/S0269889712000324

**Request Permissions :** [Click here](#)

# Biobricks and Crocheted Coral: Dispatches from the Life Sciences in the Age of Fabrication

*Sophia Roosth*

*Harvard University*

*E-mail: roosth@fas.harvard.edu*

## Argument

What does “life” become at a moment when biological inquiry proceeds by manufacturing biological artifacts and systems? In this article, I juxtapose two radically different communities, synthetic biologists and Hyperbolic Crochet Coral Reef crafters (HCCR). Synthetic biology is a decade-old research initiative that seeks to merge biology with engineering and experimental research with manufacture. The HCCR is a distributed venture of three thousand craftspeople who cooperatively fabricate a series of yarn and plastic coral reefs to draw attention to the menace climate change poses to the Great Barrier and other reefs. Interpreting these two groups alongside one another, I suggest that for both, manufacturing biological artifacts advances their understandings of biology: in a rhetorical loop, they build new biological things in order to understand the things they are making. The resulting fabrications condense scientific and folk theories about “life” and also undo “life” as a coherent analytic object.

I begin with two images, paired dispatches on the current state of things in biology. The pelagic photo in Figure 1 is an advertisement for Geneart, a German DNA synthesis company. I discovered this image while flipping through the program of the Fourth International Meeting on Synthetic Biology, which I was attending in Hong Kong in 2008. At the time I was three years into a four-year stretch of fieldwork among synthetic biologists, a group of biologists, engineers, and computer scientists committed to turning biology into a full-fledged engineering discipline. They aim to do so by applying three engineering principles – (1) standardization of building materials, (2) abstraction of levels of complexity, and (3) decoupling design from manufacture – to genetic sequences, functional systems, and simple organisms. Synthetic biology is a high profile, well funded, bioengineering project that has garnered much attention, both in the popular press and among science studies scholars (Keller 2009; Lentzos 2009; Mackenzie 2010; O’Malley 2009; Pottage 2006; Rabinow 2009; Rabinow and Bennett 2008). The advertisement that caught my attention 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 modular and easily composable, which they term “BioBricks.” The small print at the bottom of the advertisement reads: “Coral reefs are created



**Fig. 1.** Image taken from Geneart advertisement, 2008. Source: *The Fourth International Meeting on Synthetic Biology Conference Program*. <http://www.fas.harvard.edu/~hsdept/images/geneart.jpg>

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 advertisement 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, coral reefs may very well not be a part of “tomorrow’s biology.”

Instead, we may discern in this text a return to the architectural metaphors deployed by nineteenth-century British naturalists in their descriptions of coral reefs. Geneart’s comparison of calcium carbonate depositions to BioBricks anticipates and presupposes a sort of bio-architecture – something durable, organized, and structured – which these ostensibly uniform and mechanically produced bricks compose.<sup>1</sup> Further, the advertisement naturalizes such standard BioBricks by comparing them to polyps’

<sup>1</sup> Stefan Helmreich divides scientific thinking about coral into three periods, beginning with a Victorian preoccupation with coral reefs as living architecture, proceeding through twentieth-century attentions to coral as living communities with which to reflect on sex and embodiment, and finally to twenty-first century symbols of global environmental crisis (Helmreich 2010).



**Fig. 2.** *Hyperbolic Crochet Coral Reef* by the Institute For Figuring, with *Sea Slug* by Marianne Midelburg. Photo © The Institute For Figuring. [http://www.fas.harvard.edu/~hsdept/images/IMG\\_0546.jpg](http://www.fas.harvard.edu/~hsdept/images/IMG_0546.jpg)

calcium carbonate depositions, implying that a bottom-up approach to constructing biotic systems is something already innate to biology. That is, it imagines that biology has *always been* standardizable and engineerable. Synthetic biologists' BioBricks, on this view, are only slightly tweaked versions of natural modes of biotic growth and organization.

The sort of biology pictured in Figure 2 is altogether different from that of Geneart. This astonishing image arrived on my doorstep in March 2007, when Margaret Wertheim and her twin sister, Christine Wertheim, who together run the non-profit "Institute For Figuring" and helm the "Hyperbolic Crochet Coral Reef," mailed postcards publicizing the exhibition of their Reef at the Andy Warhol Museum in Pittsburgh. The Hyperbolic Crochet Coral Reef (HCCR) is a distributed collective of thousands of craftspeople who are collaboratively fabricating material models of marine life forms and evolutionary theories. They do so by pairing low-dimensional topology with handicraft techniques. The photograph of the crocheted Reef, rendered in striking shades of chartreuse and heliotrope, accompanies the following 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.

At first glance, the whimsical Hyperbolic Crochet Coral Reef bears little resemblance to synthetic biology, with its modernist functionalism, obsession with biological control, and swarming ethicists and policymakers. Yet juxtaposing the monumental brickwork of synthetic biology and the colorful fabrications wrought by the Wertheim twins and their army of women crafters sheds light on a mode of manufacture currently ascendant in the life sciences. Aside from their arresting visual affinity, these paired images denote two sorts of engagements with the biological.<sup>2</sup> One mode is unrepentantly future-oriented and fantasizes about “tomorrow’s biology.” The other is engaged in a kind of biological nostalgia, in which the unraveling of our ecosystem is paired with a renewed effort to demonstrate how the global biological has always been knitted together. Nonetheless, I take them both as examples of the direction toward which the life sciences has veered in the post-genomic era.

If genetics, genomics, and recombinant DNA technology in the 1980s and 1990s imagined organisms to be simple, decodable, and controllable, then, as Evelyn Fox Keller puts it, a “funny thing happened on the way to the holy grail” (Keller 1995). The discourse of gene action had figured DNA as code for half a century (Kay 2000). But after the Human Genome Project, biologists faced with volumes of raw sequence data were at a loss as to what came next. Instead of the genome, the post-genomic age has seen scientists turning their attentions to biological complexity: proteomes, metabolomes, metagenomes, expressomes, and microbiomes. Fields such as systems biology rejected reductionist models of biology, asking how biological forms and processes take shape in complex and evolving multiscalar interactions. While much discussion around post-genomic biology has centered on complexity, I here identify an additional feature of post-genomic biology: life is now best understood through its fabrication.

Despite their obvious institutional, demographic, and financial discrepancies, synthetic biology and the HCCR share this attribute, as I show below. For both, manufacturing biological artifacts advances their understanding of biology: in a rhetorical loop, they build new biological things in order to understand the things they are making, such that technical and epistemic work is rendered indistinguishable. The resulting fabricated objects condense scientific and folk theories about “life.” Further, when biological things are fabricated, whether by knitting together threads of DNA or skeins of yarn, practitioners identify their particular tactics as inherent in

<sup>2</sup> By biology, I here refer both to biology the substance – cells, tissues, genetic material, whole organisms – and biology the scientific discipline.

biology *prior* to their own interventions. As I suggest, the biological features synthetic biologists and Reef makers fasten on are determined by their manufacturing methods, which they then identify with the thing made. In the age of biological fabrication, technique is built into living substance, then interpreted as a quality already essential to biology (cf. Landecker 2007).

Michel Foucault claimed that “life itself” is a category that “did not exist” prior to the nineteenth century (Foucault 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).<sup>3</sup> That is, biology as a discipline was warranted by a classificatory decision: carving up the world into that which was organic and that which was inorganic, and claiming that the living world demanded a science of its own.

Contemporary biology is indebted to a long history of manipulating organic things in the service of experimentation and classification. Throughout the twentieth century, making new forms of laboratory 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 (Rader 2004, 14). Angela Creager’s history of the tobacco mosaic virus emphasizes that laboratory tools and model organisms are mutually constitutive, developing only in interaction with one another (Creager 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* alongside the course of genetics research (Kohler 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 (Landecker 2007). The difference between these examples and contemporary projects such as synthetic biology is that making new living things is now an end in itself, not something done in service to discovery science and experimental research.

In recent decades, seismic shifts in the institutional, political, and legal structures underwriting how biology is capitalized upon have had serious impacts on how biological substances ramify in novel globalized economies (Cooper 2008; Fortun 2008; Franklin 2007; Rose 2007; Sunder Rajan 2006; Taylor et al. 1997). The instrumentalization of life – via cloning and genomics technologies honed in the 1990s (Duster 2003; Goodman et al. 2003; Keller 2000; Rabinow 1999; Reardon 2004; Thacker 2005), the growing currency of bioprospecting (Hayden 2003), new reproductive technologies (Davis-Floyd and Dumit 1998; Franklin 1997; Franklin and Ragoné 1998; Ginsburg and Rapp 1995; Hartouni 1997; Strathern 1992a, 1992b;

<sup>3</sup> François Jacob announced both the rise and fall of “life” in *The Logic of Life*. He claims that before the nineteenth century, “the concept of life did not exist” (Jacob 1993, 89), but ends by admitting that “biologists no longer study life today” (ibid., 299).

Thompson 2005), and “life” rendered in digital media (Helmreich 1998; Stevens 2010; Thacker 2004) – has altered biological plasticity, relatedness, propagation, form, and potential. Both a condition for and an effect of biology in the post-genomic age, or what I here term the “age of fabrication,” is that “life” is now an epistemic category examined and understood through its manufacture: to paraphrase synthetic biologists on the cover of *Nature*, “life” simply becomes “what we make it.”<sup>4</sup>

But what does “life” become when it is defined by those making new instantiations of it? In my ethnographic work, I have tracked the deformations and reconfigurations life has undergone in a broad spectrum of locales, ranging from bioengineering laboratories to restaurant kitchens in which biochemical techniques and tools are pressed into culinary service (Roosth 2010). In what follows, I juxtapose two radically different communities, synthetic biologists and Hyperbolic Crochet Coral Reef crafters, in search of common ground. I suggest that manufactured life, more than simply blurring distinctions between nature and artifice, incarnates accumulated biological theories of life. “Life” as an analytic object has come undone, such that, when life can be manufactured, what counts as “life” is defined retroactively according to the techniques used to make it.

### Tomorrow’s Biology?

Synthetic biology is a decade-old research initiative that 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, 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 2009, when I wrapped up fieldwork conducted primarily in laboratories in MIT’s Department of Bioengineering and Computer Science and Artificial Intelligence Laboratory (CSAIL), 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 (Bhutkar 2005).

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, bioweapons, and cheap drug synthesis (Andrianantoandro et al. 2006; Church 2005; Forster and Church 2007; Purnick and Weiss 2009). The most

<sup>4</sup> The cover of a special issue of *Nature* devoted to synthetic biology (November 2005) bore the byline “Life Is What We Make It.”

prominent – and mediagenic – example of recent synthetic biology work is Berkeley Professor Jay Keasling’s development of a synthetic microbial pathway to synthesize inexpensive artemisinin, an anti-malarial compound, for distribution in developing countries (Ro et al. 2006). Another notable synthetic biology project is the work of the J. Craig Venter Institute (JCVI) to synthesize a “minimal” organism (Gibson and Benders et al. 2008), a single-celled, independently living entity that maintains, JCVI researchers posit, the minimum amount of genetic information necessary to sustain life. 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. Venter exulted that his team had made “the first self-replicating species we’ve had on the planet whose parent is a computer” (Wade 2010).<sup>5</sup> If synthetic biologists now define life through its material construction, then the minimal organism becomes a receding horizon: it is not the simplest, smallest, and most genetically austere organism found on earth, but the most genetically minimal viable organism that can be built.

The Synthetic Biology Working Group comprised two laboratories at MIT that were, while I was doing my fieldwork between 2005 and 2009, at the forefront of the burgeoning synthetic biology movement. The first lab was headed by Drew Endy, who, in addition to running his lab at MIT and a DNA synthesis company called “Codon Devices,” also co-founded and directed the BioBricks Foundation, which promoted the Open-Sourcing of standardized biological parts. Over the course of my time in his MIT lab, I watched as Endy’s star rose, and both his doctoral students and synthetic biology skeptics described him to me as a charismatic and “larger than life” “religious figure” whose name grew indissociable from the new research initiative he was working to popularize. The principal investigator of the second laboratory at MIT was Tom Knight, a CSAIL research scientist. When I first met Knight, who is affiliated with Science Commons and other Open Source groups, he had already been at MIT for over forty years. He arrived in the early 1960s at the age of fourteen and never left.

One of the central projects of this group was outlining a series of community-approved standards that would set guidelines for the composition and assembly of genetic sequences, objects they term “BioBricks.” The MIT-based Registry of Standard Biological Parts catalogs all such standardized genetic sequences; it currently comprises around 5,100 genetic parts. Practitioners store BioBricks both digitally in an online catalog and physically in freezers at MIT’s Registry of Standard Biological Parts. The parts cataloged in the Registry must meet community-approved standards, including the insertion of genetic prefixes and suffixes and the use of approved plasmids and

<sup>5</sup> This organism was not, however, *de novo* life – much more than computers was necessary to “parent” this creature. The nucleotides used in synthesis no 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.

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 openly among researchers, who in turn are expected to share either sequence data or actual DNA with each other. As the slogan of the BioBricks Foundation, which was plastered on t-shirts, bumper stickers, and the signature lines of synthetic biologists' emails, repeatedly enjoined me: "Share your parts!"

Synthetic biologists 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. That is, while the design and assembly of synthetic biological systems is *not* standardized, synthetic biologists' aim is that standardized components will allow researchers to use the same BioBrick on multiple projects, rather than testing by trial and error whether functional genetic components will work together each time they begin a new engineering project. They imagine parts or whole systems may soon be ordered from "biofabs" or "foundries," DNA synthesis companies that fabricate made-to-order genetic sequences. The manufacture and distribution of these BioBricks among synthetic biologists constitutes a "moral economy" of researchers dedicated to building, modifying, and exchanging these parts (Kohler 1994; Shapin 1988; Thompson 1971). BioBricks are built by synthetic biologists, and are almost exclusively used by synthetic biologists rather than "traditional" life scientists. Over seventy academic laboratories are currently enrolled Registry users. Synthetic biologists' dedication to Open Source approaches to bioengineering is underwritten by BioBricks' putative modularity, as practitioners value collaboration and sharing and posit that standardizing genetic sequences will engender "openness." The standardization of BioBrick parts, they hope, will standardize the ethos of openness among current and future synthetic biologists. These built biotic artifacts are at once technical objects and social tools that orient and organize the synthetic biology community.

In his history of drosophila geneticists from 1910 to 1940, Robert Kohler demonstrated that the exchange of fruit flies among researchers engendered the standardization of model organisms. In the case of synthetic biology, this order is reversed. Synthetic biologists build standardization into the system from the get-go in the interest of cultivating free exchange. Their approach is radically different from much of the current bioengineering terrain, which seeks to commercialize and capitalize on new biotechnologies. Synthetic biologists align themselves with an intellectual property doctrine closer to that of Free Software and Open Source adherents than that of most other biotechnologists today. When I once asked Drew Endy why he was so passionate about Open Sourcing biology, he responded, "I don't want wheat fields in 2010 to operate like Windows 95." On this view, one shared by many researchers with whom I spoke, openness allows for an iterative process that will engender "better" biology, as researchers work together to tweak, debug, and improve upon a system. According to this logic, standardization breeds openness, openness furthers standardization, and

the combination leads to “better” biology.<sup>6</sup> Synthetic biologists work to embed the technical and practical norms they want to ground their movement in the objects that they make. Through the work of making and assembling standardized biological 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. That is, the people and the parts are mutually composed, as the parts condition the sociality synthetic biologists hope to realize.

Paul Rabinow has characterized synthetic biology as “a return of the organism . . . as an object of reformation” or “remediation” (Rabinow 2006). Perhaps this is so. 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.<sup>7</sup> If the various genome projects of the 1990s – for humans, mice, dogs, fruit flies, yeast, tomatoes, flu virus, grapes – sedimented the genome as the signature of a particular species, then synthetic biologists are building a heteroclite taxonomy of parts and devices that genetically draw together diverse species and socially draw together a community of practitioners devoted to and defined by BioBricks’ propagation. An example clarifies this point. In 2006, I watched a group of MIT undergraduates, repulsed by the malodor of bacterial cultures, build bacteria that smelled like banana and wintergreen. This biological system constituted 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 living things synthetic biologists freely exchange are composed of trans-species 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 BioBricks online and store them in the Registry’s freezer in Cambridge. Transgenic critters, such as strawberries bearing fish genes, have been troubling categories of relatedness – species, lineage, and consanguinity – for some time, as scholars such as Sarah Franklin (2007) and Donna Haraway (1997) have noted. They “fit into well-established taxonomic and evolutionary discourses and also blast widely understood senses of natural limit. What was distant and unrelated becomes intimate” (Haraway 1997, 56).

Indeed, 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 radically – think of Borges’s Chinese Encyclopedia. Parts from yeast, petunias, snapdragons, bioluminescent marine bacteria, *Arabidopsis*, and fairy fan flowers appear under their Linnaean nomenclature.

<sup>6</sup> For an account of how free software adherents think similarly about Open Source software yielding “betterness,” see Keltz 2008.

<sup>7</sup> Certainly, the eclipse of the organism is not limited to synthetic biology. As Manfred Laubichler argues in “The Organism is Dead. Long Live the Organism!,” in the twenty-first century, biology reoriented itself in the wake of the Human Genome Project from a reductionist, mechanistic science to a holistic one (Laubichler 2000).

However, 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). To further complicate things, parts borrowed from another researcher are sourced to the names of the researchers that gifted these parts, delineating a kind of lab pedigree. For example, one such pedigree reads: “We thank Natalia . . ., Department of Horticulture and Landscape Architecture, Purdue University for the gift of the expression vector with the petunia *BSMT1* coding sequence.”<sup>8</sup> Biotic and social modes of circulation and relatedness, and natural and artificial origins and exchanges, here hybridize.

The resulting living artifacts, in which species boundaries deliquesce in transgenic exchanges of yeast and petunias, reflect and underwrite social exchanges of biomaterials. 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 ever more parts. In an essay on new biotechnologies, Freeman Dyson compared such genetic minglings to 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)

Dyson’s comparison of genetic exchanges, couplings of petunias and *E. coli*, to the circulation of intellectual property and material artifacts echoes Haraway’s reminder 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 the organisms into which they will be inserted, promise other kinds of circulation, unbound from intellectual property regimes. Or at least, so the synthetic biological imagination claims. Synthetic biologists draw together not only diverse species, but also knit together the researchers who are arguing about, assembling, modifying, and sharing their parts. Genetic and social sorts of circulation and relatedness remake and reflect one another in the fabricated artifacts of twenty-first century bioengineering.

Alain Pottage has argued, in language that calls to mind Foucault’s formulation of “life itself,” 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.” Whereas biotechnology, simply put, has sought to functionalize and

<sup>8</sup> [http://partsregistry.org/Part:BBa\\_J45004:Design](http://partsregistry.org/Part:BBa_J45004:Design) (last accessed August 15, 2012).

instrumentalize existing living things and biological processes, synthetic biology would both sort living things according to digital organization strategies and synthesize new genetic components not found in nature (Pottage 2006, 144–146). Whether synthetic biologists' ambitions are "realized" or not, their project 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.

## **A Fragile Monster**

What could such a high-stakes, highly funded field as synthetic biology have in common with a collaborative, grassroots, handicraft project? Over three thousand crafters have helped fabricate The Hyperbolic Crochet Coral Reef, with the aim of raising awareness of how fragile marine ecosystems are imperiled by anthropogenic climate change. The Reef currently has two incarnations – the first is the wooly one, described by the Wertheims as "an on-going evolutionary experiment" in which crafters rear "an ever-evolving crochet 'tree of life'."<sup>9</sup> The second, plastic reef is an invocation of the Great Pacific Garbage Patch, a swirling mass of plastic detritus that waxes as silicon-based coral reefs wane. The Wertheim twins describe it as an "evil twin to yarn-based reefs; a malevolent synthetic analog to the delicate fiber-forms."<sup>10</sup> As one reef looks back to living systems imperiled and at risk, the second, like synthetic biology, prognosticates synthetic futures. If "synthetic," for synthetic biologists, means something assembled, as in "synthetic chemistry," the Great Pacific Garbage Patch is synthetic in the senses of artificial, human-made, and unnatural.

Crochet is a traditional handicraft that uses a single hook to thread loops through other loops. Cornell mathematician Daina Taimina discovered in 1997 that by adding stitches at a constant rate, one could crochet a three-dimensional model of hyperbolic geometry. Hyperbolic geometry, which is a non-Euclidean geometric manifold that defies Euclid's parallel postulate, has a constant negative curvature. It had long proven extremely difficult to understand, let alone physically model, even though filter-feeding marine animals, not to mention frilly plant leaves and fungi gills, approximate hyperbolic morphologies, which maximize the permeable and absorptive surface of an organism while minimizing the body's interior. Margaret Wertheim emphasizes coral reefs' imminent endangerment while also referencing the deep time of coralline evolution. In a public lecture, she showed her audience photographs of nudibranchs and flatworms, pronouncing: "Here are two creatures who have never heard of Euclid's

<sup>9</sup> Available at <http://crochetcoralreef.org/about/index.php> (last accessed August 15, 2012).

<sup>10</sup> Available at [http://crochetcoralreef.org/about/toxic\\_reef.php](http://crochetcoralreef.org/about/toxic_reef.php) (last accessed August 15, 2012).

parallel postulate, didn't know that [it] was impossible to violate, and they're simply getting on with it. They've been doing it for hundreds of millions of years."<sup>11</sup>

The Reef now makes itself at home in art-science ecotones: it broods in the Ocean Hall of the Smithsonian's National Museum of Natural History and in the Hayward Gallery in London; it runs riot on the pages of both *Science* and *Crochet Fantasy*. The original crocheted reef has bred multiple satellite reefs, which flourish in craft circles and workshops around the world – Capetown, Sydney, Riga, Dublin, Chicago, New York. The fifty crafters who have contributed most to the Reef include artists and professional craftspeople, as well as a math teacher, several computer programmers, a librarian, a retired geneticist, and a sheep farmer.

The Hyperbolic Crochet Coral Reef first took shape in 2005 when Margaret Wertheim, a science writer and native of Queensland, and her sister Christine Wertheim read about Taimina's fibrous geometric models. They began crocheting their own hyperbolic geometries. For months, they followed Taimina's simple algorithm, until Christine Wertheim, growing restless, began to drift from mathematical exactitude, increasing stitches at whim. To her sister, "The effect was electrifying. Suddenly the models came to *life* – they began to look like natural organisms instead of Platonic ideals."<sup>12</sup> When the Wertheims noticed that the hyperbolic forms they had crocheted evoked the organisms of the Great Barrier Reef, they solicited contributions on their website, asking that, like the cumulative work of coral polyps, crafters join them in spawning a crocheted coral reef. The models, made of yarn and plastic, are certainly not "alive" in any biotic sense. To what kind of fabricated "life," then, does Margaret Wertheim here refer, and how might it compare to the "life" synthetic biologists manufacture?

Throughout the twentieth century, theoretical biology has been marked by a penchant for using mathematical and geometric formalisms as either descriptions of or explanations for the ways in which living bodies grow and evolve in interaction with their surrounding environments. Scholars such as D'Arcy Thompson, C.H. Waddington, Brian Goodwin, J.B.S. Haldane, Stuart Kauffman, and Humberto Maturana each articulated theories of biological growth, form, and formalism mathematically. Twentieth-century biology is littered with examples of such mathematical thinking, ranging from cellular automata (Varela, Maturana and Uribe 1974) to L-systems (Kelty and Landecker 2004) to biocybernetics (Asaro 2007; Keller 2008; Pickering 2010). However, while the Reef originated in non-Euclidean geometry, it did not, for its crafters, "come to life" until they deviated from mathematical principles. On their view, the spark of life resides in creative, accidental, or fortuitous swerves *away* from mathematical formalism.

<sup>11</sup> Wertheim, The Beautiful Math of Coral. Available at: [http://www.ted.com/index.php/talks/margaret\\_wertheim\\_crochets\\_the\\_coral\\_reef.html](http://www.ted.com/index.php/talks/margaret_wertheim_crochets_the_coral_reef.html) (last accessed October 12, 2012).

<sup>12</sup> Available at [http://www.theiff.org/reef/contributors/christine\\_wertheim.html](http://www.theiff.org/reef/contributors/christine_wertheim.html) (emphasis in the original; last accessed October 12, 2012).

Reef crafters explicitly treat the process of crocheting hyperbolic geometries as an analog for biological evolution. This analogy traffics both ways: Reef crafters describe Darwinian and neo-Darwinian evolution – the manner in which organisms are slowly shaped by or attuned to their environment via the accumulation of genetic alterations – as akin to craft. Further, they understand craft as a practice analogous to evolution in its slowness and gradual modification. Margaret Wertheim explains that Reef makers

have gradually evolved a wide taxonomy of hyperbolic crochet “species.” To our surprise, the range of possible forms seems to be endless, yet they all result from extremely simple instruction sets. Just as the teeming variety of living species on Earth result from different versions of the DNA-based genetic code, so too a huge range of crochet hyperbolic species have been brought into being through minor modifications to the underlying code. As time progresses the models have “evolved” from the simple purity of Dr. Taimina’s mathematically precise algorithms to more complex aberrations that invoke ever more naturalistic forms.<sup>13</sup>

Anita Bruce, a British crafter with degrees in both zoology and textile arts, describes the process by which she “evolves” plankton forms she knits out of scientific wire:

I look at evolution – the elegantly simple mechanism that creates biodiversity. My “specimen” life forms are hitherto unrecorded creatures that dwell in the depths of the ocean. I look at how life is catalogued, classified and displayed. . . . Over the past few years I have conducted what I think of as a series of experiments using the principles of mutation to evolve new textile “life forms.” Over time, new “species” of these organisms come into being as the patterns and underlying codes evolve.<sup>14</sup>

Other contributors have similarly begun articulating their craftwork using evolutionary terminology. Margaret Wertheim describes Reef makers’ innovations as engendering “whole genera of crochet reef organisms,”<sup>15</sup> “creating several major branches on the crochet tree of life,”<sup>16</sup> rendering “wooly mutants seemingly coughed up from the stomach of some bilious leviathan,”<sup>17</sup> and “invent[ing] an entire taxonomy of ‘radiolarians.’”<sup>18</sup> She claims that multiple contributors will simultaneously stumble across the same crochet innovation while working in isolation, a process she likens to convergent evolution, the biological process by which distinct lineages share analogous structures or functions (such as wings in bats, birds, and insects). Retired geneticist and HCCR crafter Helle Jorgensen speculates as to what forms her crochet might

<sup>13</sup> Available at [http://crochetcoralreef.org/about/darwinian\\_evolution.php](http://crochetcoralreef.org/about/darwinian_evolution.php) (last accessed October 12, 2012).

<sup>14</sup> Bruce, “Knitted Plankton.” Available at <http://anitabruce.co.uk/pblog/page80/page80.html> (last accessed October 12, 2012).

<sup>15</sup> Available at [http://crochetcoralreef.org/contributors/sarah\\_simmons.php](http://crochetcoralreef.org/contributors/sarah_simmons.php) (last accessed October 12, 2012).

<sup>16</sup> Available at [http://crochetcoralreef.org/contributors/helen\\_bernasoni.php](http://crochetcoralreef.org/contributors/helen_bernasoni.php) (last accessed October 12, 2012).

<sup>17</sup> Wertheim and Wertheim, “Chicago Cultural Center, Gallery Guide Essay.”

<sup>18</sup> *Ibid.*

take if she were “crocheting in another world with non-carbon based life and different physical laws,” and describes the forms that recur in her crocheted artifacts, writing, “We have learnt the meaning of organic shapes, textures and colours occurring in Nature, for survival. Evolution?”<sup>19</sup> More grandiloquently, an anonymous Reef crafter enigmatically named “Dr. Axt” proclaims, “If hyperbolic figures represent the rhythm of life then I am the center of the Universe.”<sup>20</sup>

In both synthetic biology and the Hyperbolic Crochet Coral Reef, practitioners regard the techniques they use as intrinsic to biology, identifying their own tactics, whether of streamlining, engineering, standardizing, or crocheting, as fundamental features of biology that precede their interventions. If synthetic biologists build standardized, rational, or minimal biological objects in order to *persuade* themselves that life might be standardizable, partible, or even Open-Sourceable, the people crocheting the Reef also identify their techniques with biology by figuring evolution as akin to craft practice. Evolution and craftwork, according to this thinking, are both protracted affairs, by definition unpredictable, improvisatory, transformative, entangled, and materials-based. In the mid-twentieth century, cybernetics and information theory snuck teleological stories about evolution into biology. Synthetic biologists who fantasize about “optimizing” biological design recognize post-genomic complexity while remaining committed to the ambitions of a mathematically inflected formalized biology. Reef contributors reject such notions altogether, instead mimicking evolutionary complexity through their manufacture of new coralline forms.

For the thousands of women who have fabricated the Reef, fabrication is a mode of improvisational, materially exploratory craftwork, a grappling with biological things apprehended by their manufacture. Simulating oceanic morphologies renders biology something whose evolutionary unfoldings crafters not only mimic, but also analogically generate, through an ad hoc crafting of new crochet forms. The result is a composite, materially-instantiated evolutionary theory – that is, the Reef itself demonstrates how error, adaptation, and interspecies relations drive changes in living form and function while calling attention to how anthropogenic climate change imperils the health of marine ecologies. Reef makers’ repetitive gestures recapitulate the protracted piecemeal depositions of polyps and their improvisations offer a tangible understanding of morphogenesis. Their wooly corals are hybrid and freeform crafted objects. So too are their evolutionary yarns.

Projects such as the Reef indicate a new sort of engagement with biological things, one whose characteristics, I posit, are not limited to the two examples discussed here, but can increasingly be found in professional laboratories and research centers. This approach is about apprehending biology not only materially, but also in and through its collaborative making. Both synthetic biologists and Reef crafters construe biology as a process – specifically, an evolutionary one – that, like crafting, tends

<sup>19</sup> Available at [hellejorgensen.typepad.com/gooseflesh](http://hellejorgensen.typepad.com/gooseflesh) (last accessed October 12, 2012).

<sup>20</sup> Available at [http://crochetcoralreef.org/contributors/dr\\_axt.php](http://crochetcoralreef.org/contributors/dr_axt.php) (last accessed October 12, 2012).

to be changeable, error-prone, messy, and risky. As Drew Endy often reminded his students, the contingencies of four billion years of evolution have developed living systems that are not easy to understand. The task of synthetic biology, he believes, is to optimize and streamline evolved organisms. Whereas synthetic biologists aim to rationalize evolution, Reef makers instead simulate evolutionary unpredictability. The project is, in the Wertheims' words, "a collective experiment in textile-based evolution."<sup>21</sup> In both cases, practitioners advance their understandings of biology by manufacturing biological forms, whether out of DNA or yarn. In the age of biological fabrication, life is best understood by making it.

Importantly, in both cases, the products are cultural artifacts that embed notions of how biology works, as well as claims about how biology *should* work. This fact suggests that all biotechnical and bioengineered entities in the age of biological fabrication – including, perhaps especially, those currently being manufactured in high-powered laboratories such as those at MIT, the Lawrence Berkeley Laboratory, or the J. Craig Venter Institute, are *material instantiations of sums of biological theories*. In the last two decades, researchers have taken the biological knowledge accumulated over the last two centuries and installed it into newly manufactured biological artifacts. These objects do not represent biological theories; they literally incorporate them – form them into bodies. Life scientists and their allies may build new biological things to learn more about biology, but they also try to install their theories, apprehensions, faiths, and preconceptions in the objects they manufacture.

## Biological Facts and Artifacts

Making new biological things is, for synthetic biologists and Reef crafters alike, "the royal route to an understanding of" biology (Keller 2009). Their approach 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 manufacturing methods as inherent in biology prior to their own interventions. The "postvital" turn in twentieth-century molecular biology, as it is periodized by Richard Doyle, meant the collapse of the body onto "a transparent sequence that has nothing behind or beyond it" (Doyle 1997, 13). But this is the postvital in the post-genomic moment. 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.

Making and modeling life, whether in eminent laboratories or humbler locales, entails a rhetorical transaction in which practitioners posit that biology has always been amenable to their constructive impulses. They go so far as to say that biology exhibits

<sup>21</sup> Wertheim and Wertheim, "Chicago Cultural Center, Gallery Guide Essay."

those interventions they themselves perform: biology, for synthetic biologists, operates like an engineer. For Reef crafters, it proceeds in a kind of knitting. In making such claims, they destabilize life as an object of investigation. Life becomes dispersed into technique, as practitioners identify their own methods as qualities essential to “life itself.”

At the tail of the twentieth century and the twenty-first’s head, life’s investigation became progressively amenable to constructive approaches. Remember synthetic biologists’ pronouncement that “life is what we make it.”<sup>22</sup> Lorraine Daston and Peter Galison speculate that science recently has transitioned from an age of scientific *representation* to one of *presentation*, in which the acts of “making and seeing are indistinguishable” (Daston and Galison 2007, 46). Extending their claim into biology, I suggest that biological knowing and biological making, paired under the twin signs of the biologically factual and the biologically artifactual, are now mutually constitutive. More than pointing to an absence of any coherent referent for “life,” this trend demonstrates that not only is “life itself” something richly constructed, but so is biological substance. Now is certainly not the first time biological things are being made: prominent earlier examples include the pigeon fanciers of Darwin’s day, hybrid corn in the 1930s and 40s, and laboratory model organisms from tobacco mosaic virus to drosophila. However, for synthetic biologists and Reef crafters, making new living things is not a means to an epistemic end, but the end in itself. Making here operates in a dialectical relationship with the epistemic work of investigation, examination, and analysis. Simply put, people now *build biotic things in order to understand the things that they themselves are making*. As “life itself” deliquesces and recrystallizes, reforms and deforms, in the hands of contemporary life scientists, the relations between making and knowing are also reconfigured, with serious consequences for the stories we tell about nature and artifice, analysis and synthesis.

## Acknowledgements

Thanks to Michael Fischer, Stefan Helmreich, David Kaiser, Heather Paxson, Astrid Schrader, Susan Silbey, Alma Steingart, Kaushik Sunder Rajan, and two anonymous reviewers for reading and commenting on this article. I am also grateful to members of the Harvard Department of the History of Science for offering feedback and guidance. The research and writing of this article was supported by grants from the Wenner-Gren Foundation (Grant No. 7928) and the National Science Foundation Doctoral Dissertation Research Improvement Grant (Award No. 0847853). Finally, I thank the synthetic biologists and Reef makers who generously shared their work with me.

<sup>22</sup> See fn 4.

## Reference List

- Andrianantoandro, Ernesto, Subhayu Basu, David K. Karig, and Ron Weiss. 2006. "Synthetic Biology: New Engineering Rules for an Emerging Discipline." *Molecular Systems Biology* 2:1–14.
- Asaro, Peter. 2007. "Heinz von Foerster and the Bio-Computing Movements of the 1960s." In *An Unfinished Revolution? Heinz von Foerster and the Biological Computer Laboratory, 1958–1976*, edited by Albert Müller and Karl H. Müller. Vienna: Edition Echoraum.
- Bernauer, Hubert. 2005. *SYNBIOLOGY: An Analysis of Synthetic Biology Research in Europe and North America*. Literature and Statistical Review. European Commission Framework Programme (FP6). Final report by NEST (New and Emerging Science and Technology): FP6-2003-NESTB4 Project 015357 – SYNBIOLOGY.
- Bhutkar, Arjun. 2005. "Synthetic Biology: Navigating the Challenges Ahead." *Journal of Biolaw & Business* 8(2):19–29.
- Church, George M. 2005. "Let Us Go Forth and Safely Multiply." *Nature* 438(7067):423.
- Cooper, Melinda. 2008. *Life as Surplus: Biotechnology and Capitalism in the Neoliberal Era*. Seattle: University of Washington Press.
- Creager, Angela. 2002. *The Life of a Virus: Tobacco Mosaic Virus as an Experimental Model, 1930–1965*. Chicago: University of Chicago Press.
- Daston, Lorraine, and Peter Galison. 2007. *Objectivity*. New York: Zone Books.
- Davis-Floyd, Robbie, and Joseph Dumit, eds. 1998. *Cyborg Babies: From Techno-Sex to Techno-Tots*. New York: Routledge.
- Doyle, Richard. 1997. *On Beyond Living: Rhetorical Transformations of the Life Sciences*. Stanford: Stanford University Press.
- Duster, Troy. 2003. *Backdoor to Eugenics*. New York: Routledge.
- Dyson, Freeman. 2007. "Our Biotech Future." *New York Review of Books* 54(12):24–29.
- Forster, Anthony C., and George M. Church. 2007. "Synthetic Biology Projects *In Vitro*." *Genome Research* 17(1):1–6.
- Fortun, Michael. 2008. *Promising Genomics: Iceland and deCODE Genetics in a World of Speculation*. Berkeley: University of California Press.
- Foucault, Michel. 1971. *The Order of Things: An Archaeology of the Human Sciences*. New York: Pantheon Books.
- Franklin, Sarah. 1997. *Embodied Progress: A Cultural Account of Assisted Conception*. New York: Routledge.
- Franklin, Sarah. 2007. *Dolly Mixtures: The Remaking of Genealogy*. Durham: Duke University Press.
- Franklin, Sarah, and Helena Ragoné, eds. 1998. *Reproducing Reproduction: Kinship, Power, and Technological Innovation*. Philadelphia: University of Pennsylvania Press.
- Gibson, Daniel, Gwynedd Benders, et al. 2008. "Complete Chemical Synthesis, Assembly, and Cloning of a Mycoplasma Genitalium Genome." *Science* 319(5867):1215–1220.
- Ginsburg, Faye, and Rayna Rapp, eds. 1995. *Conceiving the New World Order: The Global Politics of Reproduction*. Berkeley: University of California Press.
- Goodman, Alan, Deborah Heath, and M. Susan Lindee, eds. 2003. *Genetic Nature/Culture: Anthropology and Science Beyond the Two-Culture Divide*. Berkeley: University of California Press.
- Haraway, Donna J. 1997. *Modest\_Witness@Second\_Millennium.FemaleMan\_Meets\_OncoMouse: Feminism and Technoscience*. New York: Routledge.
- Haraway, Donna J. 2003. *The Companion Species Manifesto: Dogs, People, and Significant Otherness*. Chicago: Prickly Paradigm.
- Hartouni, Valerie. 1997. *Cultural Conceptions: On Reproductive Technologies and the Remaking of Life*. Minneapolis: University of Minnesota Press.
- Hayden, Cori. 2003. *When Nature Goes Public: The Making and Unmaking of Bioprospecting in Mexico*. Princeton: Princeton University Press.
- Helmreich, Stefan. 1998. *Silicon Second Nature: Culturing Artificial Life in a Digital World*. Berkeley: University of California Press.

- Helmreich, Stefan. 2010. "How Like a Reef: Figuring Coral, 1839–2010." In *Party Writing for Donna Haraway*, a Webfestschrift, edited by Katie King (commissioned by Sharon Ghamari-Tabrizi), <http://reefhelmreich.blogspot.com/> (last accessed October 12, 2012).
- Jacob, François. 1993. *The Logic of Life: A History of Heredity*. Princeton: Princeton University Press.
- Kay, Lily. 2000. *Who Wrote the Book of Life? A History of the Genetic Code*. Stanford: Stanford University Press.
- Keller, Evelyn Fox. 1995. *Refiguring Life: Metaphors of Twentieth-Century Biology*. New York: Columbia University Press.
- Keller, Evelyn Fox. 2000. *The Century of the Gene*. Cambridge MA: Harvard University Press.
- Keller, Evelyn Fox. 2008. "Organisms, Machines, and Thunderstorms: A History of Self-Organization, Part One." *Historical Studies in the Natural Sciences* 38(1):45–75.
- Keller, Evelyn Fox. 2009. "What Does Synthetic Biology Have to Do with Biology?" *BioSocieties* 4(2):291–302.
- Kelty, Christopher, and Hannah Landecker. 2004. "A Theory of Animation: Cells, L-systems, and Film." *Grey Room* 17:30–63.
- Kelty, Christopher. 2008. *Two Bits: The Cultural Significance of Free Software*. Durham: Duke University Press.
- Kohler, Robert. 1994. *Lords of the Fly: Drosophila Genetics and the Experimental Life*. Chicago: University of Chicago Press.
- Landecker, Hannah. 2007. *Culturing Life: How Cells Became Technologies*. Cambridge MA: Harvard University Press.
- Laubichler, Manfred. 2000. "The Organism is Dead. Long Live the Organism!" *Perspectives on Science* 8(3):286–315.
- Lentzos, Filippa. 2009. "Synthetic Biology in the Social Context: The UK Debate to Date." *BioSocieties* 4(2):303–315.
- Mackenzie, Adrian. 2010. "Design in Synthetic Biology." *BioSocieties* 5(2):180–198.
- O'Malley, Maureen A. 2009. "Making Knowledge in Synthetic Biology: Design Meets Kludge." *Biological Theory* 4(4):378–389.
- Pickering, Andrew. 2010. *The Cybernetic Brain: Sketches of Another Future*. Chicago: University of Chicago Press.
- Pottage, Alain. 2006. "Too Much Ownership: Bio-prospecting in the Age of Synthetic Biology." *BioSocieties* 1(2):137–158.
- Purnick, Priscilla E.M., and Ron Weiss. 2009. "The Second Wave of Synthetic Biology: From Modules to Systems." *Nature Reviews Molecular Cell Biology* 10(6):410–422.
- Rabinow, Paul. 1999. *French DNA: Trouble in Purgatory*. Chicago: University of Chicago Press.
- Rabinow, Paul. 2006. *The Biological Modern*. Concept Note. Anthropology of the Contemporary Research Collaboratory, February 2. [http://anthropos-lab.net/documents/concept\\_labor/the-biological-modern](http://anthropos-lab.net/documents/concept_labor/the-biological-modern) (last accessed October 12, 2012).
- Rabinow, Paul. 2009. "Biopower, Dignity, and Synthetic Anthropos." *National Humanities Center's On The Human Forum*. 8 June. <http://onthehuman.org/2009/06/biopower-dignity-synthetic-anthropos/> (last accessed October 12, 2012).
- Rabinow, Paul, and Gaymon Bennett. 2008. "From Bioethics to Human Practices, or Assembling Contemporary Equipment." In *Tactical Biopolitics: Art, Activism, and Technoscience*, edited by Beatriz da Costa, 389–400. Cambridge MA: MIT Press/Leonardo Books.
- Rader, Karen. 2004. *Making Mice: Standardizing Animals for American Biomedical Research, 1900–1955*. Princeton: Princeton University Press.
- Reardon, Jenny. 2004. *Race to the Finish: Identity and Governance in an Age of Genomics*. Princeton: Princeton University Press.
- Ro, Dae-Kyun, et al. 2006. "Production of the Antimalarial Drug Precursor Artemisinin Acid in Engineered Yeast." *Nature* 440(7086):940–943.

- Roosth, Sophia. 2010. "Crafting Life: A Sensory Ethnography of Fabricated Biologies." Ph.D. diss., Cambridge MA: MIT.
- Rose, Nikolas. 2007. *The Politics of Life Itself*. Princeton: Princeton University Press.
- Shapin, Steven. 1988. "The House of Experiment in Seventeenth-Century England." *Isis* 79(3):373–404.
- Stevens, Hallam. 2010. "Life Out of Sequence: An Ethnographic Account of Bioinformatics from the ARPANET to Post-Genomics." Ph.D. diss., Cambridge MA: Harvard University.
- Strathern, Marilyn. 1992a. *After Nature: English Kinship in the Late Twentieth Century*. Cambridge: Cambridge University Press.
- Strathern, Marilyn. 1992b. *Reproducing the Future: Essays on Anthropology, Kinship, and the New Reproductive Technologies*. New York: Routledge.
- Sunder Rajan, Kaushik. 2006. *Biocapital: The Constitution of Postgenomic Life*. Durham: Duke University Press.
- Taylor, Peter, Saul Halfon, and Paul Edwards, eds. 1997. *Changing Life: Genomes, Ecologies, Bodies, Commodities*. Minneapolis: University of Minnesota Press.
- Thacker, Eugene. 2004. *Biomedica*. Minneapolis: University of Minnesota Press.
- Thacker, Eugene. 2005. *The Global Genome: Biotechnology, Politics, and Culture*. Cambridge MA: MIT Press.
- Thompson, Charis. 2005. *Making Parents: The Ontological Choreography of Reproductive Technologies*. Cambridge MA: MIT Press.
- Thompson, Edward Palmer. 1971. "The Moral Economy of the English Crowd in the Eighteenth Century." *Past & Present* 50:76–136.
- Varela, Francisco, Humberto Maturana, and Ricardo Uribe. 1974. "Autopoiesis: The Organization of Living Systems, Its Characterization and a Model." *BioSystems* 5:187–196.
- Wade, Nicholas. 2010. "Synthetic Bacterial Genome Takes Over a Cell, Researchers Report." *New York Times* May 21:17.