Microbes as Machines: Life, Control, and the Problem of Scale in the Emergence of Nanotechnology

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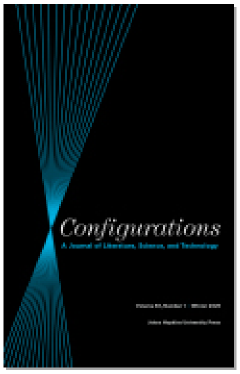

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Microbes as Machines: Life, Control, and the Problem of Scale in the Emergence of Nanotechnology

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ABSTRACT: This article re-examines claims made around nanotechnology early in its conception in order to retrospectively highlight questions at the core of that discourse that remain relevant today. Early nanotechnology rhetoric paradoxically invokes the capacities of microbes as proof of concept, even as nanoscientists dream of creating far more complex modes of building and intervention at the nanoscale. This article traces this contradictory trope through the history of nanotechnology, including a reading of Drexler's *Engines of Creation*, Feynman's "There's Plenty of Room at the Bottom," the Drexler–Smalley debate, and the idea of "self-assembly." I demonstrate how microbial capacities bring into view but also cover over questions about the nature of technological control, how we define life, and what is possible at the nanoscale. Throughout, the dreams of precise control at the nanoscale are contrasted to an alternative vision presented by Lynn Margulis and Dorion Sagan that also situates microbes as technological but does so to present a vision that reworks or even displaces human control.

The First Biotechnologists and the Actual Nanomachines

In their 1986 book *Microcosmos*, Lynn Margulis and Dorion Sagan perform a surprising reappropriation of the term "biotechnology":

> [Bacteria] invented all of life's essential, miniaturized, chemical systems—achievements that so far humanity has not approached. This ancient high *bio-*

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> technology led to the development of fermentation, photosynthesis, oxygen breathing, and the removal of nitrogen gas from the air. It also led to worldwide crises of starvation, pollution, and extinction long before the dawn of larger forms of life.[1]

Here Margulis and Sagan rewrite the terms of technoscience as a continuation of the operations already developed by bacteria in order to resituate the claims of humanity as engineers of life within the capacities already presented by prokaryotes.

In the same year (1986), K. Eric Drexler claims the same microbial functions for his similarly astonishing yet different vision of technology in *Engines of Creation.* The first invocation is a subtle yet powerful periphrasis as he introduces what he popularizes there as “nanotechnology.” In the middle of a description of molecular activities he slips in the phrase: “More complex patterns make up the active nanomachines of living cells.”[2] Without explanation, cellular components are named nanomachines, which “biochemists already work with.”[3] In fact, “genetic engineers are already showing the way” for a nanotechnology that, for Drexler, leads to a future that includes a post-scarcity economy, immortality, and humans in space.[4]

Between around 1990 and 2010, the visions of Drexler and others generated a flood of hype based on radical ideas of a nanotechnological future, but also a proliferation of academic publications and new funding streams under the banner of nanotechnology.[5] I myself benefited from this excitement, finding my way into science studies through an undergraduate course funded by an NSF grant studying the societal implications of nanotechnology and working as an un-

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[1] Lynn Margulis and Dorion Sagan, *Microcosmos: Four Billion Years of Evolution from Our Microbial Ancestors* (U. California Press, 1986), p. 28.

[2] K. Eric Drexler, *Engines of Creation: The Coming Era of Nanotechnology* (Anchor, 1986), p. 5.

[3] Ibid., p. 6.

[4] Ibid.

[5] For an overview, see David M. Berube, *Nano-Hype* (Prometheus Books, 2009). Matthew Kearnes and Phil Macnaghten (“Introduction: (Re)Imagining Nanotechnology,” *Science as Culture* 15, no. 4 [2006]: 279–90) point out that the inclusion of social science funding in nanotechnology was heralded as innovative and a way to avoid the mistakes of past technological initiatives. This infusion of funding did indeed provide new considerations of the role of the humanities and social sciences in considering developing technologies, but in a way that sometimes created issues. For example, as Alfred Nordmann and Arie Rip (“Mind the Gap Revisited,” *Nature Nanotechnology* 4, no. 5 [2009]) argued, the attempt to integrate ethical considerations into the nanotechnology conversation led to the uncritical import of many assumptions, which I aim to revisit in this article.

dergraduate "nanoscholar" at the University of South Carolina's Nanocenter.[6] In the middle of my time in graduate school, the excitement over nanotechnology disappeared. More academic books and publications continued to be produced, but the significance was no longer what it had been. "Nano" became a prefix used by some scientists and engineers and a few journals, but the original excitement no longer seemed to hold.

One side effect of this bubble is that, in retrospect, it has been hard to distinguish what, if anything, was significant about nanotechnology. Since the early rhetoric was built on confusingly overinflated claims, it has been difficult to analyze what nanotechnology says about conceptions of technology or if the introduction of nanotechnology actually represented a shift in the history of technoscience.[7] Drexler's claims aside, some of the early statements about the radical nature of nano remain alluring. For example, Colin Milburn provocatively claimed "nanotechnology may actually be in the process of demolishing the anthropic concept of control entirely."[8] In another vein, Valerie Hanson argued that techniques of nanoscale visualization created a newly object-based conception of atoms, making them feel like objects that can "be grasped and physically moved."[9] A third observation relates to how nanotechnology transforms conceptions of life, such as the claim by Charles Ostman that the "very definition of life" is changed by nanotechnology.[10] On this point, early scholars hesitated; when Otavio Bueno examined how physics and biology meet in nanoscience, he remained less enthusiastic, noting that "mo-

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[6] This early work was completed primarily under the guidance of Kevin C. Elliott and Pat Gehrke. Gehrke published his work on nanotechnology as Gehrke, *Nano-Publics: Communicating Nanotechnology Applications, Risks, and Regulations* (Palgrave Pivot, 2018).

[7] To be clear, I am not suggesting scholars writing at this time were uncritically caught up in the hype of nanotechnology. To the contrary, work early in the 2000s largely analyzed rather than perpetuated the hype. My point is that because such criticism had to be, to some extent, counterpoised to the hype of nanotechnology, it was difficult to see larger claims about the significance of nanotechnology as anything more than perpetuating the sensational and less careful claims brought by nanotechnology's pioneers.

[8] Colin Milburn, *Nanovision: Engineering the Future* (Duke U. Press, 2008), p. 166.

[9] Valerie L. Hanson, *Haptic Visions: Rhetorics of the Digital Image, Information, and Nanotechnology* (Parlor Press, 2015), p. 52.

[10] Quoted in Nathan Brown, *The Limits of Fabrication* (Fordham U. Press, 2017), p. 36. Similarly, Marcovich and Shinn note "questions that are associated with the origins, evolution, and functioning of life routinely include objects and forces situated at the nanoscale." Anne Markovich and Terry Shinn, *Toward a New Dimension: Exploring the Nanoscale* (Oxford U. Press, 2014), p. 92.

lecular biology and physics seem to meet in a curious, rather disjointed, way at the nanoscale."[11]

The opening quote from Margulis and Sagan provides an entry point for examining these three claims in the question of life and the nanoscale. Doing so will provide us one way to retrospectively highlight the significant rhetorical and conceptual characteristics brought by (or represented in) nanotechnology that remain even after the hype dissipated. Revisiting Drexler together with Margulis and Sagan, we can see a shared rhetorical technique at the point of their divergence: the rewriting of the bacterial, microbial, or cellular as the site of basic technological capacities. Even if they do not clearly align in practice, as Bueno claims, the languages of physics and biology collide anew in nanotechnology through the rhetoric of molecular technology, which positions questions of life or biology in relation to what can or cannot be done with atoms at the nanoscale.

While Mathias Grote also noticed this confluence of language between Margulis and Drexler and provides a history for this idea of life as technology,[12] attending to the difference between the two invocations of the microbe helps us see differences in conceptions of technology when the terms of life and technology mingle. For Margulis and Sagan, what is at stake is our ability to understand our technoscientific developments within the history of biotechnological issues already produced by bacteria. For Drexler, what is at stake is a future in which we can realize a different world, but only if we learn to manipulate molecules even more deliberately than microbes do already. Both narratives locate the crucial innovation in the microbe, but Margulis and Sagan insert the language of technology in order to infect it with the language of biology. Drexler, on the other hand, uses the language of machines to rewrite biological operations as mechanical operations. The difference becomes magnified when Margulis and Sagan pick up on Drexler's language later in *What Is Life?* (1995): "Ancient bacteria mastered nanotechnology. Already miniaturized, bacteria control specific molecules in ways of which human engineers can only dream."[13] The engineer (qua Drexler) only dreams to follow what bacteria have long been performing.

This article examines the development and implications of this mashing together of life and technology at a new scale. As we will see,

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[11] Otavio Bueno, "Representation at the Nanoscale," *Philosophy of Science* 73, no. 5 (2006): p. 189.

[12] Mathias Grote, *Membranes to Molecular Machines: Active Matter and the Remaking of Life* (U. Chicago Press, 2019), 157–69.

[13] Lynn Margulis and Dorion Sagan, *What Is Life?* (U. California Press, 1995), p. 92.

many of those who debated Drexler and his ideas in the early 2000s identified this jumping between biological and mechanical operations as a crucial issue. However, more remains to be said about how and why this confusion of biological and technological language occurs. In this context, I trace how the microbe becomes the site of a tension between the languages of biology and technology. In the texts examined here, microbes are held up as the nexus between life and nonlife, atomic components and larger scale organized entities. In this position, the microbe becomes key for both the question of deliberate manipulation of matter and the capacities of living systems.

I use the terms "rhetoric" and "rhetorical" to refer to the language, terminology, and arguments typically used within biology and physics, as well as the attendant assumptions, aspirations, and implications that arise with these discursive forms.[14] In this case, both works are invoking the same objects and operations with a similar maneuver—making biological operations into a form of technology—but they do so with different terms and claims about these operations. While I am associating Drexler's rhetoric with physics, it is specifically a mechanical physics, geared towards the task of engineering.[15] Margulis and Sagan, in contrast, invoke microbes to position them as agents and developers of these interventions. In this contrast of lan-

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14. David Berube frames his analysis of the technocratic aspects of nanotechnology as an innovative examination of the "rhetorical dynamics associated with technology," noting parenthetically that the early work in rhetoric of science borrowed unabashedly from philosophy of science ("The Rhetoric of Nanotechnology." In D. Baird, A. Nordmann, and J. Schummer, eds., *Discovering the Nanoscale* (IOS Press, 2004, 173–92), p. 174. My own method is guilty of this borrowing, being grounded in the history of semiotics and cultural theory. The point here is to analyze the basic structure of the arguments, terms, and narratives of nanotechnology in relation to life, technology, and scale in a way the observes their structure and considers the effects of those structures of arguments. I consider this methodology rhetorical in part because it has shared roots in rhetorical methods (e.g., Burke's notion of terministic screens; see Kenneth Burke, *Language as Symbolic Action,* U. California Press, 1966, p. 45). But, more importantly, it provides a way of tracing out the relationship between philosophical or even scientific considerations (how might nanoscale manipulation be described or performed?) and the broader possibility of communication about these considerations, whether amongst experts or the broader public.

15. Pieter Vermaas ("Nanoscale Technology: A Two-sided Challenge for Interpretations of Quantum Mechanics." In Baird, Nordmann, and Schummer, eds., *Discovering the Nanoscale* (above, n. 14, 72–92) notes that nanotechnology runs into less deterministic conceptions of quantum physics. He notes that nanotechnology might lead quantum physicists to determine what interpretation of quantum mechanics is appropriate for describing nanoscale behavior since such a description might be necessary for making quantum effects available for technological intervention. Such an argument provides an interesting counterpart to the argument I provide here, dealing with the (even) smaller scale conflations made by some nanotechnologists.

guage and purpose, we see the rhetorical legacy of a mechanical philosophy manifesting in a familiar way but in a new context—specifically, the operations of microbes as agents for deliberate manipulation at the nanoscale. While Margulis and Sagan morph the language of technology in order to question assumptions of human ingenuity, Drexler invokes the language of technology to map these cellular/nanoscale interactions in more classic mechanical terms. In doing so, the nanoscale generally and the capacities of microbes specifically become a site for questions about how we should understand technology writ large.

This formulation points to another exigence for this examination beyond the rhetoric of (nano)technology: a consideration of the significance of microbes as a particular object or agent brought into view by science, but which our sociotechnical imaginaries and cultural narratives still struggle to conceptualize and integrate into our sense of the world.[16] How do microbes, in their position as the smallest living systems, become caught between the philosophical assumptions of both biology and physics? From this position, a seemingly scientific problem reveals itself as a rhetorical and sociotechnical problem: How does the microbe become embroiled in the question of what is possible, both scientifically and technologically, such that arguments about both nanotechnology and biotechnology can invoke the microbe as proof of what is possible and therefore become grounds for research agendas, funding streams, and discussions of ethics and political action?

For those versed in early rhetoric of "nano," many of the texts discussed here will be familiar, including Feynman, Drexler, and the Drexler–Smalley debate, which were deliberated and analyzed at great length in that period. Tracing the figure of the microbe clarifies how nanotechnology reconfigured questions of life, control, and scale in a way that highlighted particular questions about how life works, what

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[16] Recent work in STS has been paying particular attention to the microbe. See, for example, Hannah Landecker, "Antibiotic Resistance and the Biology of History." *Body & Society* 22, no. 4 (2016): 19–52; Heather Paxson, "Post-Pasteurian Cultures: The Microbiopolitics of Raw-Milk Cheese in the United States." *Cultural Anthropology* 23, no. 1 (2008): 15–47; Paxson and Stefan Helmreich, "The Perils and Promises of Microbial Abundance: Novel Natures and Model Ecosystems, from Artisanal Cheese to Alien Seas." *Social Studies of Science* 44, no. 2 (2014): 165–93; Jamie Lorimer, *The Probiotic Planet: Using Life to Manage Life* (U. Minnesota Press, 2020); Kyla Schuller, "The Microbial Self: Sensation and Sympoiesis." *Resilience: A Journal of the Environmental Humanities* 5, no. 3 (2018): 51–66; Myra J. Hird, *The Origins of Sociable Life: Evolution After Science Studies* (Palgrave Macmillan, 2010); Allison L. Rowland, "The Human Microbiome as Visceral Commons: Resisting Rhetorical Enclosure." *Rhetoric Society Quarterly* 53, no. 3 (2023): 379–91.

it means to control via technology, and whether and how changes in scale fundamentally change these questions about control.[17]

Scaling the Gap Between Physics and Biology: Postvital Biology and the Nanoscale

The discursive tension between physics and biology has a long history that runs through conversations in systems biology, reductionist physics, and many other theories of science.[18] I want to highlight a form of that tension as it gets localized in the microbe. Margulis, Sagan, and Drexler remix the rhetoric of a moment in the history of science that Richard Doyle (1997) calls the "postvital," in which life is "recast as an effect of a molecule," DNA.[19] This postvital discourse permits biologists to use a mechanical language to describe biological operations while also preserving the language, assumptions, and expectations associated with living organisms. The cell can be construed as a domain for basic biological production while also being a mechanical, definable, and even deterministic operation. Changes in DNA become changes in organisms; manipulation of DNA becomes manipulation of biology. Drexler (1986) works from this assumption when he describes the operations within the cell as "cheap and efficient molecular machinery."[20]

Postvital biology also intensifies a shift made possible by cell theory: a focus on the nanoscale as a particularly significant scale not only for life, but also for deliberate manipulation of matter in a new and more precise way. This is Drexler's opening maneuver; he rewrites

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[17] Focusing on Drexler provides a particular view of these questions of life, scale, and technology. Historical accounts make clear the idiosyncrasies of Drexler's vision and his uneven relationship to technological developments, e.g. in microscopy or chemistry; see Patrick McCray, *The Visioneers: How a Group of Elite Scientists Pursued Space Colonies, Nanotechnologies, and a Limitless Future* (Princeton U. Press, 2017); Cyrus C. M. Mody, *Instrumental Community: Probe Microscopy and the Path to Nanotechnology* (MIT Press, 2011); Chris Toumey, "Reading Feynman into Nanotechnology: A Text for a New Science." *Techné: Research in Philosophy and Technology* 12, no. 3 (2008): 133–68. However, I argue that the tension around Drexler makes visible a particular tension in how control, life, and technology are articulated that is carried into popular imaginaries but also can still manifest in technical rhetorics even from engineers and scientists who reject Drexler's visions.

[18] For an overview of the dialectic between reductionism and vitalism see Anne Harrington, *Reenchanted Science: Holism in German Culture from Wilhelm II to Hitler* (Princeton U. Press, 1996).

[19] Richard Doyle, *On Beyond Living: Rhetorical Transformations of the Life Sciences* (Stanford U. Press, 1997), p. 8.

[20] Drexler, *Engines of Creation* (above, n. 2), p. 7.

technology (including chemistry) as imprecise because it handles "atoms in unruly herds" rather than precisely arranging atoms.[21] Drexler uses this distinction to divide technology into two kinds: "The ancient style of technology that . . . handles atoms and molecules in bulk; call it bulk technology. The new technology will handle individual atoms and molecules with control and precision; call it molecular technology."[22] This division is about the scale at which control is exerted; even if chemists and physicists have long defined and manipulated atoms, they did so en masse—i.e., at a scale larger than where atoms are defined.[23] Drexler places the emphasis for technological innovation at a particular size rather than particular operations.

Yet, what examples of technological manipulation at the nanoscale are available to point to? Here, Drexler inserts his "active nanomachines of living cells."[24] Cells are the most readily available example for deliberate and precise directing of atoms. In generalizing this example, Drexler can imagine this nanomachinery by building on the postvital emphasis on DNA: "Genetic engineers are already showing the way . . . in modern gene synthesis machines, genetic engineers build more orderly polymers . . . by combining molecules in a particular order."[25]

Given that Margulis was a microbiologist, it is unsurprising to find similar emphases in Margulis and Sagan's work: "the cell is the smallest unit of life."[26] *Microcosmos* posits that cells might even be the foundation for the distinction between life and nonlife.[27] In *What Is Life?*

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[21] Ibid., p. 3.

[22] Ibid., p. 4.

[23] Throughout this article, I use the schema of scale domains I developed in Joshua DiCaglio, *Scale Theory: A Nondisciplinary Inquiry* (U. Minnesota Press, 2021). In this context, specifically, microbes operate as the mediating systems between the nanometer scale, where atoms are coherent objects, and the micrometer scale, where cells are the primary objects. As this quote from Drexler demonstrates, scale was always central to the question of nanotechnology, but it has only been variously emphasized in terms of how or whether changing scales in this way makes a significant difference. I first encountered this argument in relation to arguments about predicting risk and toxicity at the nanoscale (e.g., Vincent Karim Bontems, "How to Accommodate to the Invisible? The 'halo' of 'nano.'" *NanoEthics*, 5, no. 2 [2011]: 175–83). Another example dealing with the same issues about inertness and activity can be found in Brown, *Limits of Fabrication* (above, n. 10), p. 62.

[24] Drexler, *Engines of Creation* (above, n. 2), p. 5.

[25] Ibid.

[26] Margulis and Sagan, *What Is Life?* (above, n. 13), p. 18.

[27] Margulis and Sagan, *Microcosmos* (above, n. 1), p. 56.

they note that “to trace life back to matter was a logical extension of the idea that all species have a common ancestor.”[28] “Matter” is equivalent to the nanoscale, at which the cell can be given the critical status as the common ancestor where spontaneous dissipative matter “reaches a critical point” and becomes living. Cells become the “minimal unit” out of which the rest of life evolves as cells use DNA, ribosomes, and proteins to self-maintain and replicate.[29]

Both texts demonstrate how, in the disruptions of the language of vitality in postvital explanations, life and technology must be redescribed at this junction, with the cell as the prime agent of life’s construction.[30] The question of what the cell can do and how becomes the bridge between these two scales of manipulability. Yet, postvital discourse does not easily extend the language of mechanics to life, but rather, in a sense, scrambles the terms of what we imagine is controllable, manipulable, discernable, and agential. Here Drexler splits from Margulis and Sagan in a way that exemplifies an important rift in possible ways of thinking about life, the nanoscale, and our ability to manipulate at that scale.

Drexler extends mechanical language to cells, but with a crucial caveat: The human genetic engineers must rely heavily on microbial “machines” to assist them in their nanoscale manipulation. He notes that, to reduce errors created from their “blind assembly process,” molecular engineers must “turn to molecular machines found in bacteria.”[31] At this point, Drexler describes cellular operations in mechanical terms, with enzymes, ribosomes, and proteins performing various operations usually performed at the meter scale: cutting, reading, gluing, writing, editing.[32] Drexler has described the cell as a fac-

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[28] Margulis and Sagan, *What Is Life?* (above, n. 13), p. 69.

[29] Ibid., p. 78.

[30] On the tension between a systems conception of nanotechnological intervention and a classic mechanical one, see G. Khushf, “A Hierarchical Architecture for Nanoscale Science and Technology: Taking Stock of the Claims About Science Made by Advocates of NBIC Convergence,” in Baird, Nordmann, and Schummer, eds., *Discovering the Nanoscale* (above, n. 14); J. Schmidt, “Unbounded Technologies: Working Through Technological Reductionism of Nanotechnology,” in Baird et al., eds., (above, n. 14); and Bueno, “When Physics and Biology Meet” (above n. 11).

[31] Drexler, *Engines of Creation* (above, n. 2), 6–7.

[32] Note that Drexler’s vision of the machine is also couched in the language of information, but remains deterministic, which is an essential aspect of postvital biology, as discussed in Richard Doyle, *On Beyond Living* (above, n. 19) and *Wetwares: Experiments in Postvital Living* (U. Minnesota Press, 2003). McCray (*Visioneers,* above, n. 17) and Grote (*Membranes,* above, n. 12) provide a historical perspective on this language of information as it becomes commonplace in the 1960s and 70s.

tory and cellular components as workers arranged for the sake of production. However, the agency of these cellular components is subsumed to the genetic engineer: "Genetic engineers can produce these objects cheaply by directing the cheap and efficient molecular machinery inside living organisms to do the work."[33] Thus, Drexler must simultaneously grant capabilities to cells and their components even as the mechanical language claims that agency for the genetic engineers.

Margulis and Sagan run into similar questions when discussing how Vladmir Vernadsky renames life as "living matter." They argue this was "no mere rhetorical ploy," but rather a moment in which Vernadsky "cut loose centuries of mystic clutter attached to the word life."[34] Margulis and Sagan argue that, in animating matter, Vernadsky is not making life mechanical but rather emphasizing life as a process that mobilizes matter in a particular way: living systems "direct and organize atoms."[35] Margulis and Sagan, however, reserve the level of action for the microbe itself as a kind of agent when they use the language of second-order cybernetics systems theory, introducing the notion of autopoiesis: "life" describes entities that are self-making.[36] Since the cell is "the smallest autopoietic structure known today," it is granted a special status in making matter into living matter.[37] This basis allows Margulis and Sagan to reassert the agency and power of microorganisms.[38] In response to conceptions of technological control like Drexler's, they argue that "we humans do not 'invent' patentable microbes through genetic recombination; rather, we have learned to exploit and manipulate bacteria's ancient propensity to trade genes."[39]

Importantly, Drexler relies on a similar idea but uses a mechanistic terminology that refuses microbial agency: the term "replicators," which he defines as "things that give rise to copies of themselves."[40] While "replicators" could provide a less mechanical language, Drexler explicitly refuses the alternative. In describing a scenario of replicat-

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33. Drexler, *Engines of Creation* (above, n. 2), p. 7.

34. Margulis and Sagan, *What Is Life?* (above, n. 13), p. 50.

35. Ibid., p. 52.

36. On Margulis's relationship to second-order cybernetics and autopoiesis, see Bruce Clarke, *Gaian Systems: Lynn Margulis, Neocybernetics, and the End of the Anthropocene* (U. Minnesota Press, 2020).

37. Margulis and Sagan, *What Is Life?* (above, n. 13), p. 78.

38. Ibid., 92–93.

39. Ibid., p. 93.

40. Drexler, *Engines of Creation* (above, n. 2), p. 23.

ing RNA, Drexler notes that "biological terms have crept into this description: since the molecules replicate, the word 'generation' seems right; the molecules 'descended' from a common 'ancestor' are 'relatives,' and the words 'growth,' 'reproduction,' 'mutation,' and 'competition,' also seem right."[41] Drexler argues that this language becomes appropriate because replication introduces evolution, but evolution "stripped to its bare essentials, free of the emotional controversy surrounding the evolution of life."[42] But what specifically is stripped away? One answer is the inaccessibility that requires agency to be assigned to the entities at the scale of the nanometer; rather than autopoietic agents producing nanoscale intervention, these replicators become "well-defined collections of atoms obeying well-understood principles and evolving in repeatable laboratory conditions."[43] In this way, Drexler can reassert human agency: "Biochemists can make RNA and protein from off-the-shelf chemicals, *without help from life*."[44] In the very description of how life makes itself, life is removed from the equation so the biochemist can be reinserted in a process of replication now described as capable of being discerned, predicted, and controlled. In attempting to avoid the "emotional controversy surrounding the evolution of life," Drexler folds the language of life into the language of mechanism in a way that displaces the activity of replication into a series of definable actions and reactions. The engineer can then take the comfortable place as the agent directing these mechanical events.

The difference between the two philosophies of nanotechnology/life is clarified in how they explicitly respond to the question of mechanism verses animism. Drexler directly refuses the language of vitality:

> The ancient myth of a magical life-force . . . has spawned a meme saying that replicators must violate some natural law. This simply isn't so. Biochemists understand how cells replicate and they find no magic in them. Instead, they find machines supplied with all the materials, energy, and instructions needed to do the job. Cells *do* replicate; robots *could* replicate.[45]

Drexler reduces vitalism to an ambiguous magical force, which is refuted by our ability to describe how cells replicate. But here, this de-

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[41] Ibid., p. 24.

[42] Ibid.

[43] Ibid.

[44] Ibid., p. 25. Emphasis added.

[45] Ibid., p. 54.

scription is placed in mechanical terms: biochemists find "machines" operating with material components and clear instructions.

In their discussion of animism, Margulis and Sagan critique this mechanistic conception, noting how "the last outposts of animism—living organisms—yielded to the philosophy of mechanism"[46] in which mechanisms "don't act; they react."[47] In response, Margulis and Sagan argue not for a return to animism, which they contend blurs the distinction between life and nonlife, but for a renewed examination of the operations of life.[48] They again emphasize autopoiesis, the "self-making" of cells, which positions life as a scalar mediation in which the microbe arranges molecules to form and perpetuate itself. In Drexler, life is cut out even as cells and self-replication are invoked, while Margulis and Sagan redefine life in terms of processes of a microscale system coordinating nanoscale operations. Both could be said to be postvital in that they refuse some magical essence for life, but Drexler does so in a way that reduces the actions of cells to nanoscale, mechanical operations. In Margulis and Sagan's articulation, "the agency of cells" does not mean to treat cells as persons (or other humanist ideas of free will or the like) but is specifically about the kind of action, degree of complexity, and modes of building involved at this scale in order to bring molecules into the larger systems called "life." Placing Drexler next to Margulis and Sagan helps us see that, in leaving out life, Drexler leaves out the kinds of intervention and agency he nonetheless already assumed in his invocation of microbes as nanomachines.

The contrast between these two approaches points to a problem in what happens to some essential tenets of "life" when these questions about life are operationalized at the nanoscale in the capacities of microorganisms or, from the opposite direction, the operations of microorganisms are invoked as a mechanical operation. At that nexus—where microbes intervene in the nanoscale—this question of living matter reframes the question of how we describe agency and intervention. How does anyone, cells or engineers, deliberately manipulate matter? Why is it manipulation and in what sense is it deliberate? For what (system) are the atoms intervened in, how, or by whom? Does it make a difference where agency is positioned or how we describe this manipulation?

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[46] Margulis and Sagan, *What Is Life?* (above, n. 13), p. 5.

[47] Ibid., p. 7.

[48] For a discussion of Margulis's positions on mechanistic philosophy, see Clarke, *Gaian Systems* (above, n. 36), p. 174.

Conjuring the Inevitable Out of the Gap: Feynman's Three Elisions

The questions just posed are immediately obscured within the discourse of nanotechnology through an adjacent maneuver: a turn to proof of concept. When this contradictory invocation of biology is deployed as proof of the inevitability of nanotechnology, early nanotechnologists turn our focus to a simpler conception of "what is possible" that relies on this conflation of biology and physics. This maneuver can be traced to Richard Feynman's retrospectively influential "There's Plenty of Room at the Bottom." Although many nanotechnologists debated the importance of Feynman's talk (what Colin Milburn calls the "Feynman origin myth"),[49] Drexler draws his basic semiotics and vision from Feynman.[50] Most importantly, Feynman establishes this pattern in which the conflation of biology with machine is used to create a sense of inevitability. After Feynman positions his talk in the "problem of manipulating and controlling things on a small scale,"[51] he introduces the maneuver:

> I will not now discuss how we are going to do it, but only what is possible in principle—in other words, what is possible according to the laws of physics. I am not inventing anti-gravity, which is possible someday only if the laws are not what we think. I am telling you what could be done if the laws *are* what we think; we are not doing it simply because we haven't yet gotten around to it.[52]

Feynman enters a speculative register that nonetheless grounds this speculation in the laws of physics. This maneuver is interesting in itself for exemplifying a formula for future-leaning speculation that becomes central to the technocultures of the twentieth and twenty-first centuries, led by what historian Patrick McCray calls "visioneers," those who combine engineering with imagining the future.[53] This ba-

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[49] Milburn, *Nanovision* (above, n. 8), p. 36.

[50] Milburn traces this Feynman myth in an earlier article ("Nanotechnology in the Age of Posthuman Engineering: Science Fiction as Science." *Configurations* 10, no. 2 (2002): 261–95). Toumey ("Reading Feynman," above, n. 17) provides a history of how Feynman's talk gets taken up in the discourse of nanotechnology, noting its central role was partially due to Drexler's claim that Feynman was the father of nanotechnology. In that regard, we can analyze it here is an iteration of the tropes exemplified by Drexler, and thus an appropriate place to revisit to examine the maneuvers of interest.

[51] Richard P. Feynman, "There's Plenty of Room at the Bottom," *Engineering and Science* 23 (1960): p. 22.

[52] Ibid., p. 24.

[53] McCray, *Visioneers* (above, n. 17). Paola Magaudda and Stefano Crabu provide an

sic form, followed by Drexler and many other visioneers, extrapolates from existing knowledge to potential capacities.[54] This technique, which we could call the "visioneering warrant," positions the arguments within the "laws of physics" as if the question is about a straightforward application of scientific principles. Others have analyzed this maneuver in relation to a kind of technological anticipation and speculation,[55] its relationship to science fiction and culture,[56] the shaping of scientific practice,[57] and forms of sociopolitical pressure, risk, regulation, or ethics.[58]

I want to clarify how the maneuver relies on three elisions that make use of the gap between the assumptions of physics and biology to drive the sense of inevitability. Feynman's first elision is the turn to biology as a proof of concept. At a crucial point, Feynman notes that "a biological system can be exceedingly small" even as "they are very active; they manufacture various substances . . . they do all kinds of marvelous things—all on a very small scale."[59] Feynman thus adopts

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overview of STS scholarship on futures and anticipation in "Disentangling Futures from a Science and Technology Studies Perspective," *Tecnoscienza – Italian Journal of Science & Technology Studies*, 13, no. 2 (2022).

54. McCray (*Visioneers,* above, n. 17, p. 22) acknowledges this foundational maneuver in which these "ideas don't require any new physics to work," but, as a historian, does not pause to dwell on the significance of this as a rhetorical maneuver. He does discuss the historical contexts for these claims as they relate to Drexler (throughout) and Feynman (chap. 4).

55. Doyle, *Wetwares* (above, n. 32), p. 136; Colin Milburn, "The Future at Stake: Modes of Speculation in the Highest Frontier and Microbiology: An Evolving Science." In B. Clarke, ed., *Posthuman Biopolitics: The Science Fiction of Joan Slonczewski* (Springer Int. Publishing, 2020), 133–60.

56. N. Katherin Hayles, ed. *NanoCulture: Implications of the New Technoscience* (Intellect Ltd, 2004); Milburn, "Nanotechnology" (above, n. 50) and *Nanovision* (above, n. 8); Toumey, "The Literature of Promises." *Nature Nanotechnology* 3, no. 4 (2008).

57. J. Cortiel, C. Hanke, J. S. Hutta, and C. Milburn, eds. *Practices of Speculation: Modeling, Embodiment, Figuration* (transcript publishing, 2020); Zach Horton, "Toward a Speculative Nanoecology: Transscalar Knowledge, Disciplinary Boundaries, and Ecology's Posthuman Horizon." *Resilience: A Journal of the Environmental Humanities* 2, no. 3 (2015): 58–86.

58. See: Alfred Nordmann, "If and Then: A Critique of Speculative Nanoethics," *NanoEthics* 1, no. 1 (2007): 31–46; M. Kearnes, R. Grove-White, P. Macnaghten, J. Wilsdon, and B. Wynne, "From Bio to Nano: Learning Lessons from the UK Agricultural Biotechnology Controversy." *Science as Culture* 15, no. 4 (2006): 291–307; Sheila Jasanoff and Sang-Hyun Kim, eds. *Dreamscapes of Modernity: Sociotechnical Imaginaries and the Fabrication of Power* (U. Chicago Press, 2015); Kamilla Kjolberg and Fern Elizabeth Wickson, *Nano Meets Macro: Social Perspectives on Nanoscale Sciences and Technologies* (Jenny Stanford Publishing, 2010); Gehrke, *Nano-Publics* (above, n. 6).

59. Feynman, "There's Plenty of Room" (above, n. 51), p. 25.

the pattern we see in Drexler, using biological systems as a proof of concept for nanoscale intervention.

Feynman's second elision is a straightforward conception of the capacity to extend observation to the nanoscale. He notes that it should be possible to "see individual atoms" through better microscopic techniques. Curiously, he keeps his focus on examples from biology, noting that many of the "fundamental biological questions" about DNA, cell structures, or protein synthesis could be solved through a simple procedure: if you had better microscopes, then "you could just look at the thing!"[60] Seventy years later, we can note that we *do* in fact routinely look at these things using various techniques, but in a way that isn't nearly as straightforward as Feynman implies.[61] In this problematic extension, Feynman provides an early example of a trend noted by Hanson: Nanotechnology seems to reintroduce an almost Newtonian image of the atom as a visible, contained, and manipulable object—a trend only confirmed by the more recent digital interfaces imagining nanotechnology as essentially like an atomic-scale building block game.[62]

Feynman's third elision is a similar extension of human action via a simple apparatus. In one oft-cited section he describes how one might create a series of "slave hands" hooked up to a smaller set of hands, which then make smaller hands that can make smaller hands, and so on, until you're manipulating individual atoms. While Feynman acknowledges the engineering difficulties involved, this image and the language of the master-slave hands are significant for what they assume about control and intervention.[63] The master-slave hand description sets the stage for nanotechnologists to conceptualize a seamless extension of action, agency, or manipulation to the na-

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[60] Ibid., p. 24.

[61] A great deal of work has been done on this problem of visualization in biology, e.g., David Baird and Ashley Shew, "Probing the History of Scanning Tunneling Microscopy." In Baird et al., eds. (above, n. 14), 145–57; Joseph C. Pitt, "The Epistemology of the Very Small." In Baird et al., 157–64; Chris Robinson, "Images in NanoScience/Technology." In Baird et al., 173–92; Hanson, *Haptic Visions* (above, n. 9); Lorraine Daston and Peter L. Galison, *Objectivity* (MIT Press, 2010); Natasha Myers, *Rendering Life Molecular* (Duke U. Press, 2015); Philip Thurtle, *Biology in the Grid: Graphic Design and the Envisioning of Life* (U. Minnesota Press, 2018).

[62] Hanson, *Haptic Visions* (above, n. 9), p. 51. On nanotech as building block game, see Colin Milburn, *Mondo Nano: Fun and Games in the World of Digital Matter* (Duke U. Press Books, 2015).

[63] For a recent analysis of this narrative in terms of the language of slavery, see Diana Leong, "A Hundred Tiny Hands: Slavery, Nanotechnology, and the Anthropocene in *Midnight Robber*." *Configurations* 30, no. 2 (2022): 171–201.

noscale while it also, despite having invoked microbiological entities as proof, sidesteps the particularities of the entities capable of intervening at that scale. On this basis Feynman declares "we can arrange the atoms the way we want; the very *atoms*, all the way down!"[64]

For early nanotechnologists, this capacity to see and intervene seemed to be confirmed by the scanning tunneling microscope (STM), particularly following Don Eigler and Erhard Schweizer's use of the STM to create an IBM logo using single Xenon atoms. Others have analyzed the nature of this claim for the STM; I want to simply highlight that STM manipulation gives nanoscientists a simple device that preserves Feynman's three elisions and perpetuates this pair of contradictions we have been tracing.[65] To summarize, the first contradiction arises when nanotechnologists invoke cells or biological operations even as they claim the status of engineer and the agency of manipulation and intervention. The second contradiction arises when the significance of the nanoscale is invoked even as it is described in meter-scale terms and for meter-scale ends. STM manipulation is very different in form from cellular operations, and this nanoscale intervention requires additional, limited conditions that make the scalar translation of action possible. Nonetheless, Drexler performs these maneuvers repeatedly throughout *Engines*, following Feynman in using them as foundations for his sense of inevitability.[66] While the issue is, to some extent, about the "laws of physics," it is also about the assumptions physicists tend to make in talking about objects and their manipulation, which makes it possible to brush past these issues by rewriting the biological in the preferred language of mechanical physics while nonetheless invoking biological modes of intervention and agency.

Losing Life in the Nanofuture: Selective Switching Between Engineering and Microbiology in the Drexler–Smalley Debate

Nanotechnology came into legitimacy within this sheen of anticipation, relying on this anticipation to fuel funds and initiatives.[67] In the hype and counter-hype process, many early commentators attempted to examine and even refute the basic maneuvers we identified in Feyn-

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[64] Feynman, "There's Plenty of Room" (above, n. 51), p. 35.

[65] For an analysis of STM in nanotechnology, see Mody, *Instrumental Community* (above n. 17); Chris Toumey, "Probing the History of Nanotechnology." *Nature Nanotechnology* 7, no. 4 (2012); Hanson, *Haptic Visions* (above n. 9); Karen Barad, *Meeting the Universe Halfway: Quantum Physics and the Entanglement of Matter and Meaning* (Duke U. Press, 2007), p. 353–64; Daston and Galison, *Objectivity* (above n. 61), 382–84.

[66] Drexler, *Engines of Creation* (above, n. 2), p. 9.

[67] Berube, *Nano-Hype* (above, n. 5).

man and Drexler. Of interest here is whether or how those speaking for or against Drexler's vision often relied on the maneuvers just described. In this hyperbolic terrain, defining and clarifying the maneuvers proved difficult, and much of the sociotechnical imaginary made available around nanotechnology largely carried forward and perpetuated the same assumptions.[68]

One moment is instructive as it demonstrates the contradictions while leaving them unresolved and implicit: the debate between Drexler and the chemist Richard Smalley. This debate began with a popular article by Smalley, followed by a public response by Drexler, and culminated in an exchange published in *Chemical and Engineering News*.[69] The debate caused a stir within the nanotechnology conversation, with much commentary.[70] I want to revisit it to examine how the languages and assumptions of physics and biology come into tension, and how difficult it is (for Smalley, in this case) to clearly name the contradictions noted in the previous sections.[71]

Following the pattern set by Feynman, the debate is positioned as a matter of science: "Smalley does not think molecular assemblers as envisioned by Drexler are physically possible."[72] Within this frame, Drexler responds to Smalley's "sticky fingers problem" by returning to biological entities: "I find this puzzling because, *like enzymes and ribosomes*, proposed assemblers neither have nor need these 'Smalley fingers.'"[73] However, in the next paragraph, Drexler turns to engineering language, speaking of "guid[ing] the chemical synthesis of complex structures by mechanically positioning reactive molecules, not by manipulating individual atoms."[74] What is confused in this leap between ribosomes as proof and the idea of "mechanically position-

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[68] For more on the traffic of these nanophobias/philias in relation to early nanotechnology rhetoric as a "folk theory," see Arie Rip, "Folk Theories of Nanotechnologists." *Science as Culture* 15, no. 2 (2006): 349–65.

[69] Rudy Baum, "Nanotechnology: Drexler and Smalley Make the Case for and against 'Molecular Assemblers,'" *Chemical and Engineering News* 81, no. 48 (2003): 37–42.

[70] For analyses of this debate and reactions to it, see Sarah Kaplan and Joanna Radin, "Bounding an Emerging Technology: Para-scientific Media and the Drexler-Smalley Debate about Nanotechnology." *Social Studies of Science* 41, no. 4 (2011), 457–85; Chris Tourney, "Reality, Fantasy and Civility in Molecular Assemblers." *Nature Nanotechnology* 13, no. 1 (2018).

[71] The physicist Richard Jones handles some of the same issues but in a way that more fully acknowledges the problems of scale and the questions presented by life. Richard Jones, *Soft Machines: Nanotechnology and Life* (Oxford U. Press, 2004).

[72] Baum, "Nanotechnology" (above n. 69), p. 38.

[73] Ibid. p. 39.

[74] Ibid.

ing reactive molecules"? "Mechanically" indicates an external application of force (hence "positioning") to alter a set object ("molecules") that one can expect to react in the same way each time, as is usually assumed in physics and engineering. The molecules then are treated as manipulable even as they are described as reactive. These unclear assumptions make all the difference since they render the nanoscale intervention in more straightforward, meter-scale, mechanical terms while confusing the question of what is acting and how.

Smalley picks up first on Drexler's invocation of biology: "you write that assemblers will use something 'like enzymes and ribosomes.' Fine, then I agree that at least now it can do precise chemistry."[75] Smalley then adds back in aspects that come with biological entities: They have to be made within a system (e.g., cell); they must have some fluid; they need molecules available for their construction, etc. But Smalley also adds elements of the possible actions themselves: The system has to "pick" the right enzyme, "hold" it, ensure it joins at the location where this can be done, correct damage, and so on. To all this, Smalley adds limits to the kinds of chemistry it can do, noting it "can't make a crystal of silicon, or steel, or copper, or aluminum."[76] The biological-physics question is thus at the core of the problem, a point Smalley brings home when he says Drexler must be imagining a "nonaqueous enzymelike chemistry."[77] The term "enzymelike" flags how Drexler relied on a biological model even as he ignored the particularities of biology, which comes with a "long list of vulnerabilities and limitations to what it can do."[78] In short, the biology-physics distinction is invoked here to highlight the limits to interventions, action, and production at the nanoscale. Drexler has invoked the microbial but failed to consult them on what is required for being a molecular assembler.[79]

Drexler's response, however, hinges on this concern: "Although inspired by biology (where nanomachines regularly build more nanomachines despite quantum uncertainty and thermal motion), Feynman's vision of nanotechnology is fundamentally mechanical, not

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[75] Ibid. p. 40

[76] Ibid.

[77] Ibid.

[78] Ibid.

[79] This point could also be read in relation to the question about theory verses experimentalism within nanotechnology, as it is placed within Anne Johnson's discussion of computational nanotechnology ("Institutions for Simulations: The Case of Computational Nanotechnology." *Science & Technology Studies* 19:1, 2006). Johnson argues that Drexler is a theorist, but here we can see that some of what potential "theory" allows is a perpetuation of certain assumptions that rely on tentative warrants (i.e., selective comparison to biology).

biological."[80] It is astonishing that, at the very moment Drexler denies the biological connection, he reinserts the maneuver parenthetically. He must do so because the claim for inevitability rests on this renaming of microbes as nanomachines. And yet, he proceeds to contrast this biological notion to a mechanical one, what he calls "mechanosynthesis—machine-phase chemistry."[81] What is this difference Drexler imagines as "mechanical"? He goes on to describe a nanofactory system as a kind of scaled down "conventional factory system" with conveyers, positioning devices, and "computers for digitally precise control." Rather than using "solvents and thermal motion" to bring reactants together, this chemistry will use "conveyors and positioners" to create "reliable site-specific reactions."[82]

The vision here is based on meter-scale manufacturing techniques and contrasted to biology in an unclear way. The phrase "positional control itself enables a strong catalytic effect" hides the questions about what it means for molecules to be where we want them to be in a predictable and determinable fashion. For microbes to direct such intervention, living systems must have the right materials, in the right place, know how they will work, and make them do so reliably. It is no small feat to reimagine the whole process of assembling molecules from the methods biological systems have discovered. Perhaps it is possible, but it is not clear that one can do so by simply scaling down the operations familiar in the factory, which operate by managing the "unruly herds" of molecules Drexler's nanotechnology was supposed to revolutionize.

In response, Smalley turns the trope back into a contrast between two discourses we usually consider equally physical: "I see you have now walked out of the room where I had led you to talk about real chemistry, and you are now back in your mechanical world."[83] Here, it seems "chemistry" points to the particular behavior and reactions of

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[80] Baum, "Nanotechnology," (above n. 69), p. 40.

[81] "Mechanosynthesis" in many ways encapsulates the particular rhetorical configuration here that sets the goal as a straightforward physical manipulation of molecules as if they are objects to be moved and combined like meter scale objects. It still appears as a key term in nanotechnology publications, including texts on nanotechnology. For example, we see the same tropes in this quote from Jeremy Ramsden (*Nanotechnology: An Introduction,* Elsevier Science, 2011), p. 85: "Also known as molecular manufacturing or mechanosynthesis or 'pick and place' chemistry, bottom-to-bottom methods literally construct things atom by atom. In other words, it is chemistry with positional control, i.e. taking place in a eutactic environment. This is what is sometimes called 'hard' or 'true' nanotechnology (in the sense of being uncompromisingly faithful to Feynman's original vision)."

[82] Baum, "Nanotechnology," (above n. 69), p. 40.

[83] Ibid., p. 41.

the molecules and the complexities and limits of putting them together. If so, Drexler's "mechanical world" is one that imports all the worst assumptions of mechanistic philosophy: assuming all operations are performed onto external objects in a predictable, determinable, and controllable manner. In response, Smalley emphasizes that reactions between molecules cannot be thought of in these terms: "you cannot make precise chemistry occur as desired between two molecular objects with simple mechanical motion along a few degrees of freedom in the assembler-fixed frame of reference." Smalley highlights the simplification performed by the idea of a factory, countering that "you need more control." Here he brings us back to the biological—"you need something very much like an enzyme"—and notes this was why he picked up on Drexler's biological trope: to "get you to realize the limits of this approach." Drexler is thus "in a pretend world," as Smalley describes it, "where atoms go where you want because your computer program directs them to go there." But this "pretend world" is built by specifically avoiding the two issues we have raised: the particular complexities of intervention at the nanoscale as already demonstrated by apparatuses' living systems, specifically microbes and cells, who have developed methods for engineering at that scale.[84]

Ignoring the conditions of microbial action at the nanoscale makes Drexler's vision seem possible even as he invokes those conditions as proof of that same action. This is a part of the "nanovision" that Colin Milburn identifies when examining early nanotechnology rhetoric. Milburn argues that nanovision creates this sense that the future will be radically different but then provides ways to imagine or see that future and, perhaps, lead us towards it.[85] Our reexamination of these maneuvers helps us see how this imagined future was enabled by a (nano)blindness: the inability to see the extent of the scalar intervention required. This is a form of what anthropologist Anna Tsing has called "nonscalability."[86] But while Tsing argues for this nonscalability in relation to larger scales, as when businesses imagine they can scale up their operations without changing their form, the nonscal-

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[84] A parallel trope with the same issue is the idea of the nanobot. As of 2013, Toumey notes that the science fictional idea of a nanobot as a "top-down" shrunken bot does not adequately represent anything like the creations being called nanobots at the time, which were created "bottom up" in a way that is better described in the terms of biology used by Smalley.

[85] Milburn, *Nanovision* (above, n. 8), p. 13.

[86] Anna Tsing, "On Nonscalability: The Living World Is Not Amenable to Precision-Nested Scales," *Common Knowledge* 18, no. 3 (2012): 505–24; https://doi.org/10.1215/0961754X-1630424.

ability at the core of the Drexler–Smalley debate is about scaling meter-scale operations to the nanoscale. These questions about nanotechnology thus push us to examine the nonscalability at smaller scales. Manipulation at the nanoscale is different; if we consult the first nanotechnologists, then this becomes quite clear.

Life Building Itself: The Irony of Self-Assembly

In 1992, Smalley published a paper on the methods for assembling his signature buckminsterfullerenes entitled "Self-Assembly of the Fullerenes."[87] As this title suggests, the methods are described as self-assembly. This term "self-assembly" provides a final instance of the ambiguous transfer of language and assumptions between biology and engineering. Self-assembly emerges largely as an explanatory concept in biology, in descriptions of how DNA leads to more complex objects—viruses, proteins, and cells.[88] At this early moment in nanotechnology, the idea of self-assembly is imported as a key term in the movement from bulk chemistry to the precise chemistry. Drexler and Smalley's argument about the appropriate way of describing this intervention invites a more careful examination of the way "self-assembly" situates the emergence of complex structures as something inherently performed by and from those very same structures while also opening up ways for thinking through control and manipulation of those formations.

In nanotechnology, this question is often articulated as the difference between "top-down" verses "bottom-up" control, with STM as the exemplar of the former and self-assembly the latter. Smalley invokes STM first: "Scanning tunneling microscopy has a way of conjuring fanciful thoughts" in which "it is easy to imagine a whole new world down there on the chemist's atom-by-atom length scale."[89] He notes that this ability to envision such a world invites certain people to "view this world with the eyes and ambitions of a molecular architect"—in other words, with an eye to precise control. This is, of course, Drexler's vision. In contrast, when Smalley introduces fullerenes he does so through self-assembly, pointing to fullerenes as "a beautiful example of what has long been recognized to be essential for a practical nanotechnology, an efficient mechanism of self-assembly of archi-

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[87] Richard E. Smalley, "Self-Assembly of the Fullerenes," *Accounts of Chemical Research* 25, no. 3 (1992): p. 40; https://doi.org/10.1021/ar00015a001.

[88] For an early example, see D. J. Kushner, "Self-Assembly of Biological Structures." *Bacteriological Reviews* 33, no. 2 (1969): 302–45.

[89] Smalley, "Self-Assembly of the Fullerenes" (above, n. 87), p. 98.

tecturally useful structures on a nanometer scale."[90] At this moment, Smalley cites both an article on self-assembly and Drexler's *Engines of Creation*, leaving open the relationship between that vision of control provided by the STM and the notion of self-assembly.

The article about self-assembly cited by Smalley makes clear that self-assembly doesn't avoid but rather perpetuates the paradoxical invocation of biological structures. The article, by Whitesides, Mathias, and Seto, appears in a 1991 special issue of *Science*, titled "Engineering a Small World," and immediately precedes an article describing atomic manipulation using STM.[91] Before introducing self-assembly, Whitesides and colleagues position nanotechnology within biology: "To biologists, nanostructures are familiar objects. A range of biological structures—from proteins through viruses to cellular organelles—have dimensions of 1 to 10^2 nm."[92] To this they add, "To chemists, nanostructures are very large," to emphasize that "nanostructures require the assembly of groups of atoms numbering from 10^3 to 10^9."[93] The challenge is that there are simply too many atoms in any given structure to imagine unilateral top-down control. Biology's solution is at the core of the authors' primary question:

> How can one make structures of the size and complexity of biological structures, without using biological catalysts or the information encoded in genes? Nanostructures provide major unsolved problems in complexity and require new strategies and technologies for their synthesis and characterization.[94]

Here, the techniques of nanotechnology are situated in relation to biological structures but also in contradistinction to them: We want techniques that are of that size and complexity yet do not use those biological components. Their answer is then to insert into nanotechnology a term largely used in biology: self-assembly.[95]

Despite separating their ambition from biology, Whitesides, Mathias, and Seto continue to position self-assembly in relation to biologi-

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[90] Ibid.

[91] Joseph A. Stroscio and D. M. Eigler, "Atomic and Molecular Manipulation with the Scanning Tunneling Microscope," *Science* 254, no. 5036 (1991): 1319–26; https://doi.org/10.1126/science.254.5036.1319.

[92] G. M. Whitesides, J. P. Mathias, and C. T. Seto, "Molecular Self-Assembly and Nanochemistry: A Chemical Strategy for the Synthesis of Nanostructures," *Science* 254, no. 5036 (1991): p. 1312.

[93] Ibid.

[94] Ibid.

[95] A search for articles on self-assembly prior to 1990 turns up primarily articles from the life sciences, stemming from Kushner, "Self-Assembly" (above, n. 88).

cal precedents. They note: “Biology is replete with examples of complex, nanoscale structures formed by self-assembly, and living systems have mastered the art of summing many weak interactions between chemical entities to make large ones.”[96] In their conclusion, they offer biology as proof of the possibility of self-assembly they have described, listing self-assembled biological components in order to confirm that “the strategy outlined here . . . is a successful one. Biology provides countless examples; the essential principles are understood (although the details essential for applications are still murky).”[97]

But what is self-assembly? The authors define it as “the spontaneous association of molecules under equilibrium conditions into stable, structurally well-defined aggregates.”[98] Self-assembly is “spontaneous” because it is not entirely directed. Rather, certain components are present that, when put in the right situation, tend to assemble themselves into particular forms. This is quite different from STM, Feynman-style manipulation. Even if such assembling is predictable, control appears different than a usual conception of manipulation, which might be more properly conceptualized as kind of enabling by creating the appropriate conditions for their self-assembling. The complications this presents for prediction and control are apparent when biologists discuss biological self-assembly. For example, in a 1986 article, Kirschner and Mitchison note that “it is hard to imagine how we would ever be able to predict from simple principles the specific organization of microtubules in a single cell” even if we could “understand the rules that govern the overall organization of microtubules and how this organization solves a functional problem.”[99]

The definition of self-assembly displaces agency of humans even as it makes it possible to talk of intervention in a process of molecular formation. Whitesides and Boncheva (2002) make this aspect explicit: “Molecular self-assembly is a process in which molecules . . . spontaneously form ordered aggregates and *involves no human intervention.*”[100] This is not just a rhetorical point, but a technical one as it changes the techniques for crafting materials. However, we cannot neglect the

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[96] Whitesides et al., “Molecular Self-Assembly and Nanochemistry” (above, n. 92), p. 1314.

[97] Ibid., p. 1318.

[98] Ibid., p. 1313.

[99] M. Kirschner and T. Mitchison, “Beyond Self-Assembly: From Microtubules to Morphogenesis,” *Cell* 45, no. 3 (1986): p. 329.

[100] G. M. Whitesides and M. Boncheva, “Beyond Molecules: Self-Assembly of Mesoscopic and Macroscopic Components,” *Proceedings of the National Academy of Sciences* 99, no. 8 (2002): p. 4769, emphasis added.

rhetorical and philosophical implications, given the intense claims for control at the heart of nanotechnology. In an important sense, self-assembly involves no human intervention, but is rather, as the name implies, the emergence of forms by the molecular and cellular components in question. And yet, when self-assembly is integrated into nanotechnology discourse, this alteration in the position of human agency is easily obscured. Thus, in Liu et alia (2021) we find the same conflations and reassertion of the task of control. First, the invocation of biological forms: "the ability to self-assemble individual building blocks into ordered superstructures is a phenomenon known in natural systems (e.g. proteins) to gain new functionalities."[101] Then, the invocation of precision and control: "Modulating the self-assembly of superstructures in a precise and controlled manner will not only help in realizing their potential applications but also advance the fundamental understanding of self-assembly in nature."[102] Given this displacement of human intervention implied by self-assembly, we might wonder what "a precise and controlled manner" might mean. In a bewildering move, the dislocation of human intervention in self-assembly becomes associated with the radical claims for new scales and modes of control. While self-assembly might push us to reconsider what control is, its integration with the mechanical language of nanotechnology risks doing the opposite: reasserting traditional diagrams of control just when human control is displaced or might be reconceptualized.

Consulting Microbes, or, There's a Lot Already Going On at the Bottom

In the context of this displacement or reassertion of human agency built around the contradictory invocations of the microbe, we can reconsider the radical implications of nanotechnology. Returning to Colin Milburn's claim that "nanotechnology may actually be in the process of demolishing the anthropic concept of control entirely," we can wonder if and in what way this anthropic concept of control has been successfully demolished or even revised.[103] In the years following the Drexler–Smalley debate, some of the amazing dreams of Drexler have fallen to the side as researchers explore more thoroughly what is possible at this scale. The discussion of self-assembly shows, however, that these questions about the appropriate way of describing our interventions at the nanoscale remain relevant to understanding both

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[101] Dilong Liu, Rashed Aleisa, Zepang Cai, Yue Li, and Yadong Yin, "Self-Assembly of Superstructures at All Scales," *Matter* 4, no. 3 (2021): p. 927.

[102] Ibid.

[103] Milburn, *Nanovision* (above, n. 8), p. 166.

our new scales of intervention and how we conceptualize the foundations of life. Indeed, Grote comes to a similar conclusion in his history of life and technology in the same time period, noting that this era of science "transform[ed] the concept of proteins at a molecular level, thereby changing what 'biological' or 'lifelike' referred to . . . Life has been made mechanical at the molecular level by zooming in on objects that may have actually been as much chemical as biological."[104]

There is something significant about this particular scale and the particular kinds of operations performed by microorganisms that puts pressure on our conceptions of life and technology, as microbes mediate in some way between the chemical and the biological. However, the advent of these concepts of "active matter," as Grote calls them,[105] are more significant when considered in relation to the tension between Drexler and Margulis and Sagan—that is, in noticing the difference between the two articulations of technology, as I have here. Margulis has become a central figure for feminist science studies in part because her work expands notions of activity and life beyond the scales at which we usually conceptualize life. From Donna Haraway to Myra Hird,[106] Margulis has become a touchstone for rearticulating the activity of matter, and also for reworking our notions of technology.

I likewise began with Margulis and Sagan's unconventional assertion of bacteria as nanotechnologists because it is hard to find scientific articulations that do not prefer to speak in terms of human-centered control and precision. In a refreshing alternative, Margulis and Sagan attempt to reinsert microbes as the authorities we ought to consult on this issue of control and intervention of atomic arrangements. Given the ways we've seen nanotechnologists avoid this reexamination, preserve assumptions from mechanistic physics, and distort the conversation about what is physically possible, Margulis and Sagan's attempt to consult these nanotechnologists points to a different way of considering the structure and organization of microbes as well as nanotechnological intervention initiated by humans.

At stake in the rhetorical difference is whether we take seriously the operations of microbes as a particular form of activity, as well as a need to more explicitly reconceptualize the location and form of activity at the nanoscale even as we develop our capacities to intervene at this scale. With nanotechnology, a new set of technological possibilities enters the scene and also provides many insights into the foundations of biology. What is interesting is how quickly this rhetoric forced us to

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104. Grote, *Membranes to Molecular Machines* (above, n. 12), p. 180; for a history and analysis of the molecular conceptions of life, see Myers, *Rendering Life* (above, n. 61).

105. Grote, *Membranes to Molecular Machines* (above, n. 12), p. 190.

106. Hird, *The Origins of Sociable Life* (above, n. 16).

grapple with whether biology can be considered in terms of technology, or the reverse. Is it appropriate to describe biology in terms of technology and physics or the reverse, and to what implications?[107]

Clearly, there is already plenty going on at the nanoscale. Nanotechnology and biotechnology demand new articulations of what intervention at that scale looks like that are more attendant to how any description parses these relations. The stakes are both in how we practice technoscience and in how we conceptualize our practice of it. While Drexler appeared to be a new vision, I have clarified how this vision is a limited one even in its idea of being unlimited; it imagined a scale that was void of agents and easily extended into, which included the powers of life to direct assembly even as those powers were rewritten from without. In this context, Drexler's vision becomes an old vision of absolute control, the conquest of a passive (nano)landscape that renews and extends classic fantasies of total technological control without understanding the very conditions under which anything like "control" might be asserted. Work on nanotechnology and science fiction implies that these problems are not exclusive to Drexler but bleed into cultural imaginaries.[108]

I have also tried to show here, with reference to more recent examples, that these problems continue to plague articulations and conceptualizations of nanoscale engineering even by those who reject Drexler's vision. This is not to say nanoscale engineering cannot or has not continued to develop, but, in this ongoing development, this early questioning about control has largely fallen by the wayside. It remains for future work to consider how the continued development of nanoscale technological interventions might put in practice alternative conceptions of control, and whether the assumptions about life and control identified here continue to operate tacitly. In any case, we would do well to consult these first nanotechnologists and acknowledge what they actually demonstrate about nanoscale intervention. Microbes and cells do, after all, have a lot to say about the limits of this strange, dangerous, and profoundly misguided idea of technology that remains human-centered, obsessed with control, and preferentially written to erase the complex entities at many scales that make such interventions possible.

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[107] For an interesting attempt by biologists to take on these questions, see Marc Kirschnew, John Gerhart, and Tim Mitchison, "Molecular Vitalism," *Cell* 100, no. 1 (2000): 79–88.

[108] From a different direction, Nathan Brown (above, n. 10) plays with how literary forms present the same questions about the limits of fabrication; Brown provides parallel readings of poetics and attempts at nanoscale manipulation as a means of encountering how we imagine materials to be able to work and be controlled.