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Nano Dreams and Nano Worlds: The Emergence and Disciplinary Formation of Nanoengineering

A dissertation submitted in partial satisfaction of the requirements for the degree of Doctor of Philosophy

in

Communication (Science Studies)

by

Emily York

Committee in Charge:

Professor Valerie Hartouni, Chair
Professor Kelly Gates
Professor Robert Horwitz
Professor Lilly Irani
Professor Colin Milburn
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2016

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The Dissertation of Emily York is approved, and it is acceptable in quality and form for publication on microfilm and electronically:

Chair

University of California, San Diego
2016

DEDICATION

This dissertation is dedicated to Sean York, my partner, friend, and collaborator; to my parents Mike Johnson and Maria Kitscher for their unwavering support; and to my family, friends, and mentors who have supported and encouraged me in this process.

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I would also like to thank the faculty and students of the Department of NanoEngineering at UC San Diego for allowing me in to their courses, meetings, laboratories, and events. My research here was conducted with Institutional Review Board approval, under IRB 101734 and 141804.

Chapter 2 extends and elaborates on material that appears in "Nanodreams and Nanoworlds: Fantastic Voyage as a Fantastic Origin Story," *Configurations*, Fall 2015, Volume 23, Number 3, pp. 263-299. The dissertation author was the primary investigator and author of this paper.

Chapter 3 extends and elaborates on material that appears in "Smaller is Better? Learning an Ethos and Worldview in Nanoengineering Education," *NanoEthics*, August 2015, Volume 9, Issue 2, pp 109-122. The dissertation author was the primary investigator and author of this paper.

Illustrations in this dissertation are the product of a collaboration between the dissertation author and artist Sean York. The dissertation author has the full permission of Sean York to use any and all illustrations to which he contributed.

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“Smaller is Better? Learning an Ethos and Worldview in Nanoengineering Education,” *NanoEthics*, August 2015, Volume 9, Issue 2, pp 109-122.

ABSTRACT OF THE DISSERTATION

Nano Dreams and Nano Worlds: The Emergence and Disciplinary Formation of Nanoengineering

by

Emily York

Doctor of Philosophy in Communication (Science Studies)

University of California, San Diego, 2016

Professor Valerie Hartouni, Chair

This dissertation analyzes the sociotechnical practices through which nanoengineering is produced as a new disciplinary and professional site of "innovation for the benefit of society." I argue that innovation constitutes a rationalizing discourse that serves to justify the establishment of a field, department, and major. Additionally, it serves as an organizing logic that constitutes the nanoengineer as an inherently ethical actor, and nanoengineering as a benefactor of a universalized consumer-subject. I

contribute an empirically grounded feminist science studies perspective on how material and discursive practices of innovation rationalize, define, and justify a new scientific discipline; how moral and ethical reasoning is figured within technical practices and pedagogies; and how sociocultural, historical, political, and technical imaginaries figure and are themselves refigured in the constitution of nanoengineering. My analysis is based on an ethnography I conducted from 2010-2014 of one of the world's first nanoengineering departments and its new undergraduate nanoengineering major, located at the University of California, San Diego. This included observing most of the undergraduate courses; conducting 85 interviews with faculty, students, and administrators; observing a nanoengineering laboratory; participating in department meetings and events; collaborating with the department to produce a new department newsletter; and analyzing the media used in the department and curriculum. More specifically, my dissertation chapters examine how popular culture is enrolled in the consolidation of a new discipline; how a particular ethos, with a moral stance and value positions, gets taught in the context of technical education; how liberal and neoliberal logics of rational individualism, autonomy, and the invisible hand get worked into the material and discursive practices of self-assembly in the nanoengineering laboratory; how the institutional goal of producing human capital manifests in the undergraduate major in the form of entrepreneurialism; how translational research as a paradigm of innovation becomes the right tool for the job of aligning nanoengineering's commitments to innovation and utility with the institutional imperative to produce intellectual capital; and how the higher-ed science classroom is an important site for considering the ethics and politics of knowledge production. I present my work in both prose and graphic novel style narrative illustration.

Chapter 1 Introduction

> What I propose in the following is a reconsideration of the human condition from the vantage point of our newest experiences in our most recent fears. This, obviously, is a matter of thought, and thoughtlessness—the heedless recklessness or hopeless confusion or complacent repetition of 'truths' which have become trivial and empty—seems to me among the outstanding characteristics of our time. What I propose, therefore, is very simple: it is nothing more than to think what we are doing.
>
> Hannah Arendt[1]

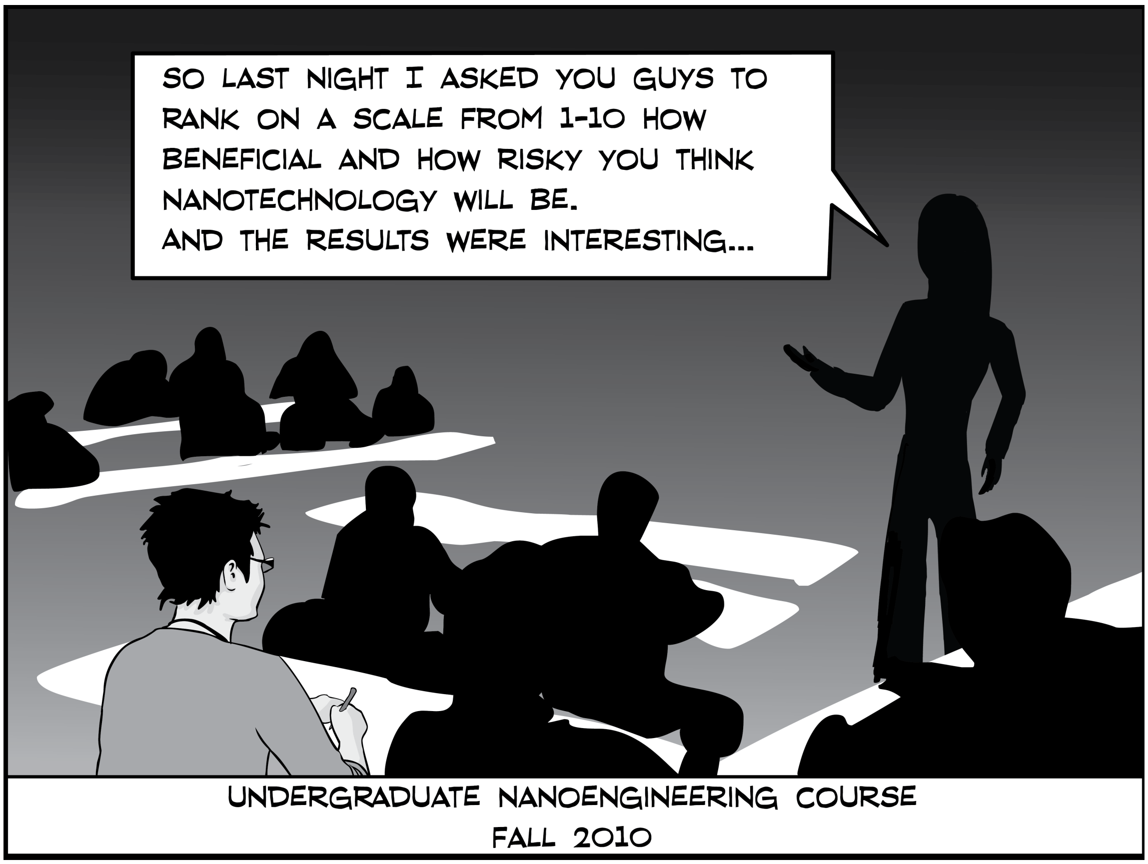

Illustration 1 Students are asked to rank how beneficial and how risky they think nanotechnology will be as part of an extra-credit assignment.

1. Hannah Arendt, *The Human Condition*, 2nd ed. Chicago: University of Chicago Press, 1998, 5.

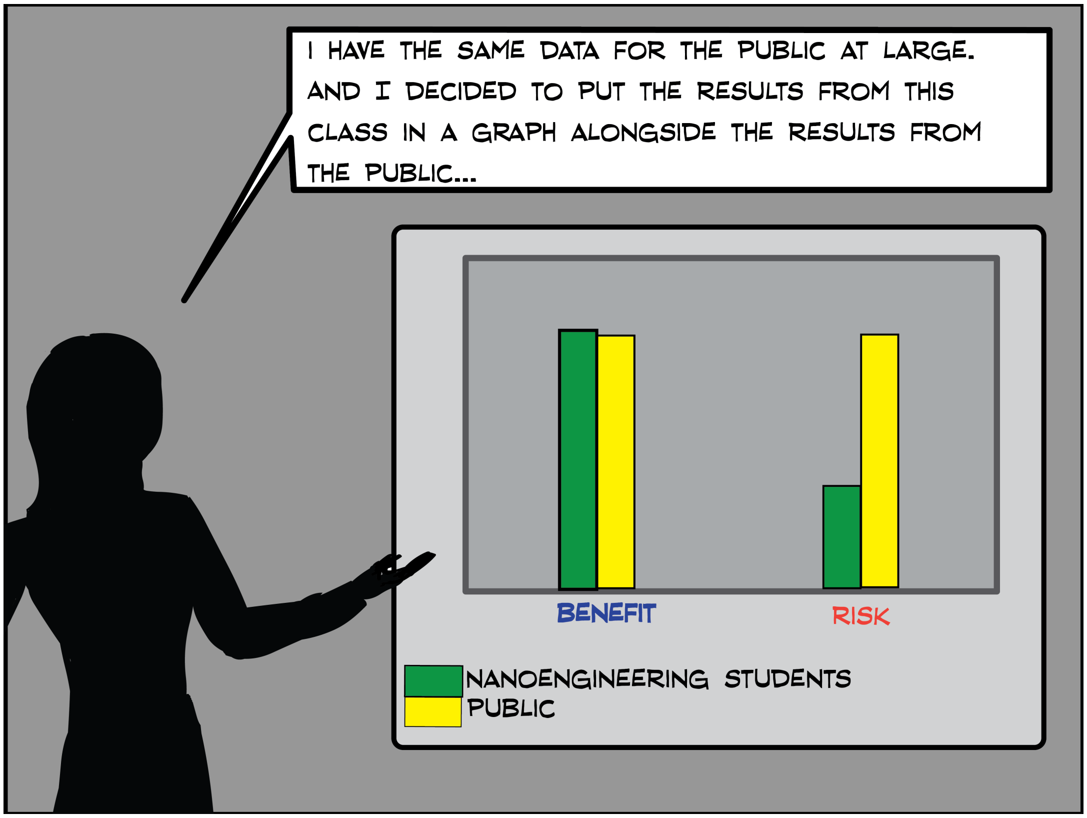

Illustration 2 The professor puts the resulting data from the class ranking alongside data taken from a public poll.

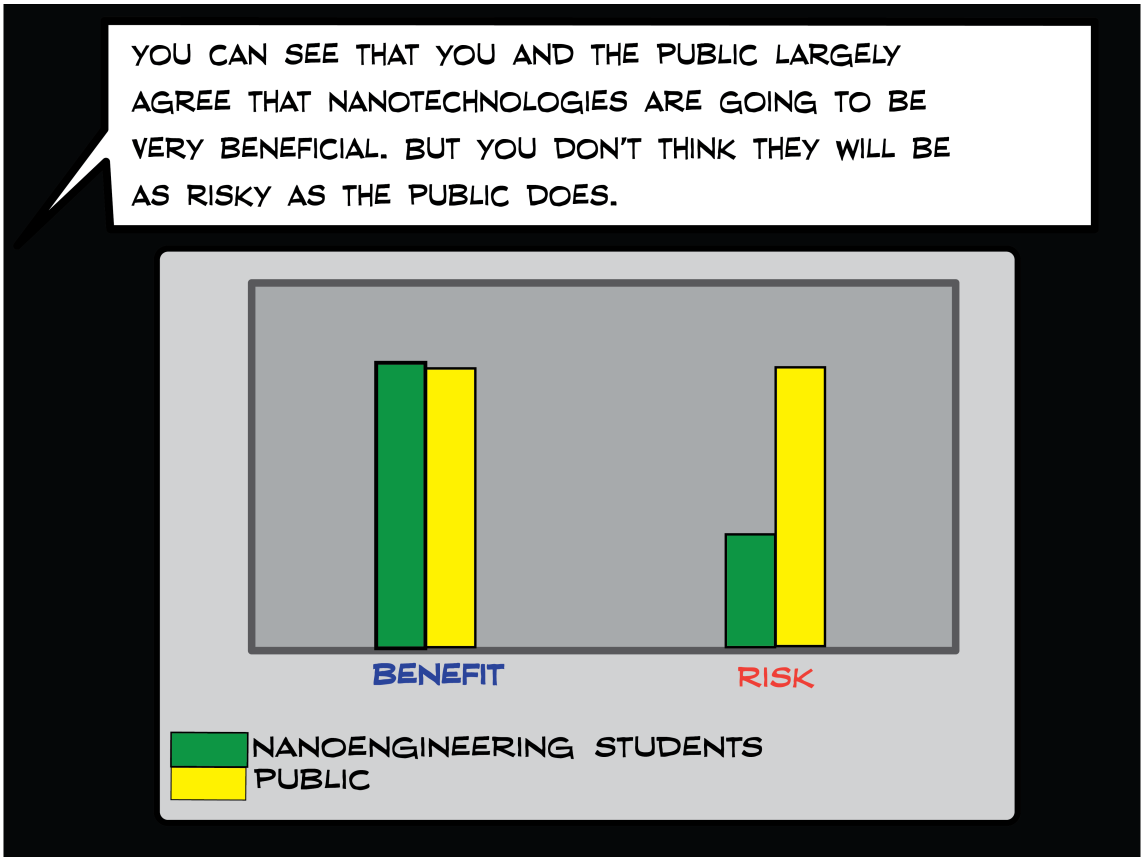

Illustration 3 Students' expectations of benefit and risk. Their expectations of benefit are quite similar to those of the public. But the students do not appear to think that nanotechnology will be as risky as the public does.

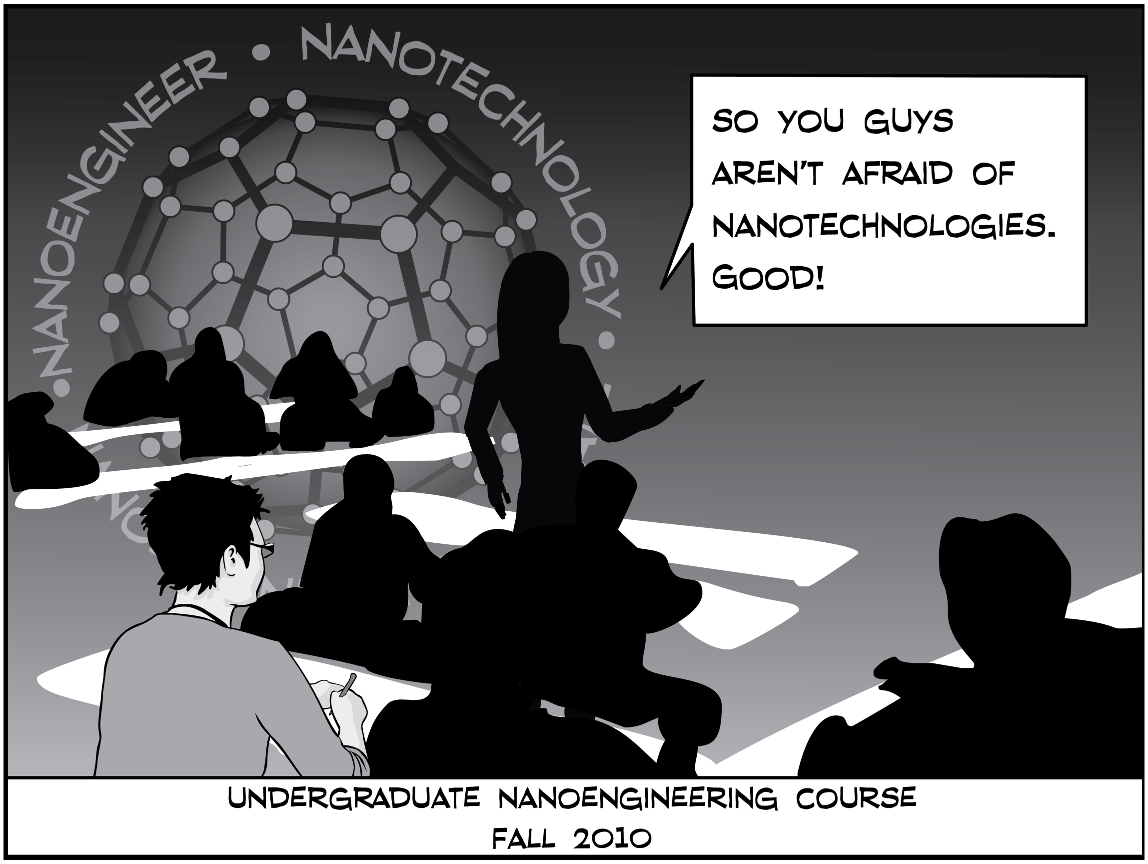

Illustration 4 The professor tells them, "So you guys aren't afraid of nanotechnologies. Good!"[2]

The above vignette presents a moment in an undergraduate nanoengineering class that is interesting on several levels. First, it marks a point of transition for these students with respect to the field of nanoengineering, from outsiders who are themselves members of the public, to insiders who are distinguished from the public. As insiders, they are to become authoritative figures on questions about nanotechnology. The difference between their assessment of the potential risks of nanotechnology and that of the public indexes

2. This opening vignette is based on my observation of a mid-level undergraduate nanoengineering class. As it is based on my notes and not an audio recording, the exact language is an approximate representation of the words spoken, although I did note the precise words, "You guys aren't afraid of nanotechnologies" and "Good!" The actual graph was more a more detailed line graph.

their success in taking on the identity of the nanoengineer and its privileged relationship to the subject of nanotechnology. Moreover, the professor has communicated that the correct stance with respect to the question at hand is that the benefits of nanotechnology will far outweigh the risks, and that any suspicion of greater risk must be grounded in fear. This fear, associated now with the public, is implicitly attributed to ignorance. Second, the framing of the question, the graph, and the brief comments communicates that technology should be evaluated according to benefit-risk ratios and that benefit and risk can be understood in universal terms that are abstracted from the specifics of who and what may or may not benefit or be at risk with respect to specific technological configurations. Third, by moving on to another subject after this brief aside rather than using it as a starting point to delve in to a more reflexive discussion about what constitutes benefit and risk, the professor misses an opportunity to engage students in a critical and thoughtful discussion about the broader societal dimensions of nanotechnologies. If this were an isolated moment, an outlier in this curriculum, it might be relatively insignificant in terms of a four-year degree program. But, as I will show, this moment is indicative of a broader set of material and discursive practices in a nanoengineering department and undergraduate major that frequently bracket social, political, and ethical questions by articulating nanoengineering as intrinsically good.

This dissertation tells a story about the emergence and disciplinary formation of nanoengineering, a set of knowledge- and world-making practices that are oriented toward the manipulation of matter on the nanoscale. The nanoscale conventionally demarcates a range between 1 and 100 nanometers, or billionths of a meter. To use an oft-cited comparison in introductions to nanotechnology, one nanometer is approximately 80,000 times smaller than the diameter of a human hair.[3]

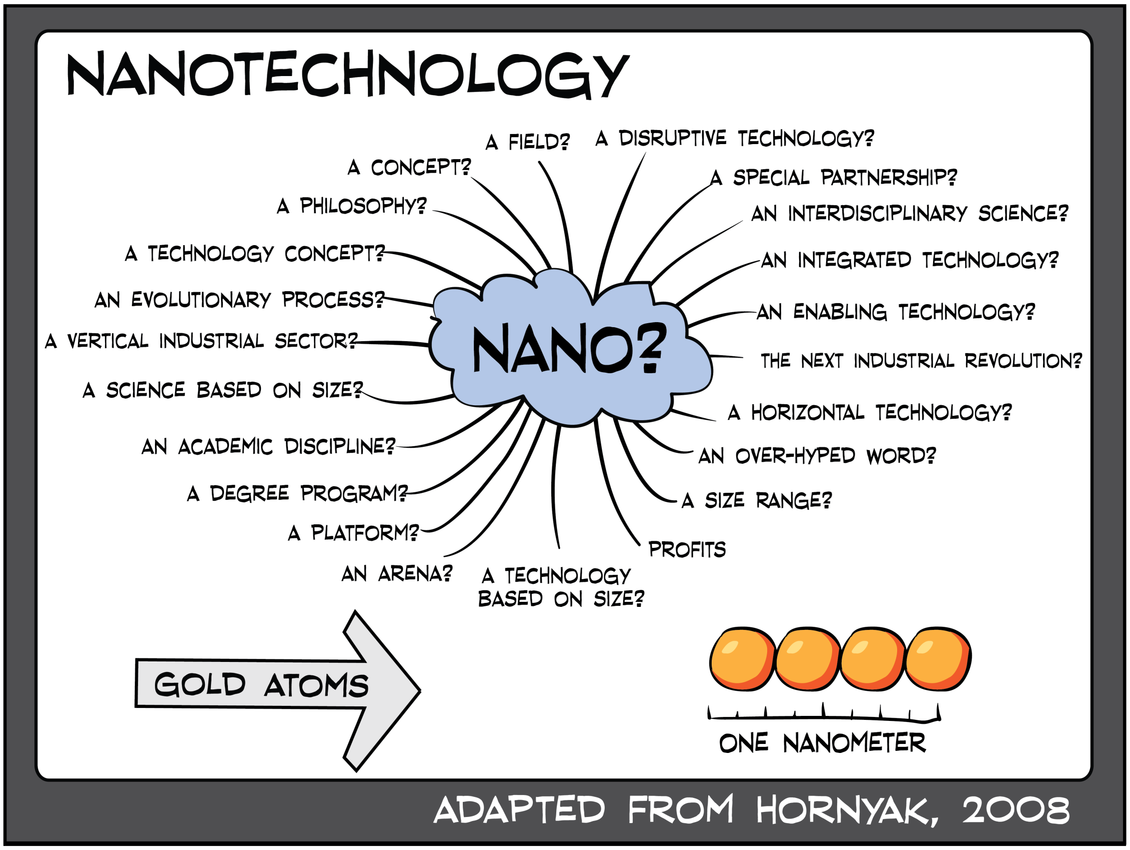

Illustration 5 Nano? This image, adapted from a nanotechnology textbook used in the curriculum, asks the question, Nano? It presents a range of possible answers, suggesting that the nano is not entirely fixed. Although there is one answer that has no question mark: Profits.

When technoscientific practices are consolidated in a disciplinary program at a university, they are constitutive of a disciplinary and professional identity that has an ethos and worldview, values and goals. This has several implications. First, one way—though certainly not the only—that values get embedded in scientific practice is through

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3. Davis Baird, Alfred Nordmann, and Joachim Schummer, *Discovering the Nanoscale*, Amsterdam ; Washington, DC: IOS Press, 2004, 232. See Baird, Nordmann, and Schummer for a specific instance of using this comparison.

the coproduction of disciplinary practices with a disciplinary and professional identity.[4] This coproduction occurs particularly in the higher education classroom, where science education—while technical—always also develops the ethos and worldview of the discipline, teaching values and goals that fundamentally inform its technical practices. Second, this coproduction of knowledge- and world-making practices, disciplinary and professional identities, and ultimately the material artifacts that emerge from these practices, entails something new, even if practices taken individually do not by themselves enact a Kuhnian rupture.[5]

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4. Sheila Jasanoff, *States of Knowledge : The Co-Production of Science and Social Order*, London ; New York: Routledge, 2004. See essays in the edited volume *States of Knowledge* for an elaboration of the term "coproduction". Jasanoff defines this term as "shorthand for the proposition that the ways in which we know and represent the world (both nature and society) are inseparable from the ways in which we choose to live in it. Knowledge and its material embodiments are at once products of social work and constitutive of forms of social life; society cannot function without knowledge any more than knowledge can exist without appropriate social supports. Scientific knowledge, in particular, is not a transcendent mirror of reality. It both embeds and is embedded in social practices, identities, norms, conventions, discourses, instruments and institutions – in short, in all the building blocks of what we term the social. The same can be said even more forcefully of technology," Jasanoff, "The Idiom of Co-Production" in *States of Knowledge,* 2-3.

5. Thomas Kuhn, *The Structure of Scientific Revolutions*, 3rd edition, Chicago, IL: University of Chicago Press, 1996. See Kuhn for an analysis of how normal and revolutionary science differs. Normal scientific research occurs within a paradigm, whereas a rupture signifies the transformation of such a paradigm.

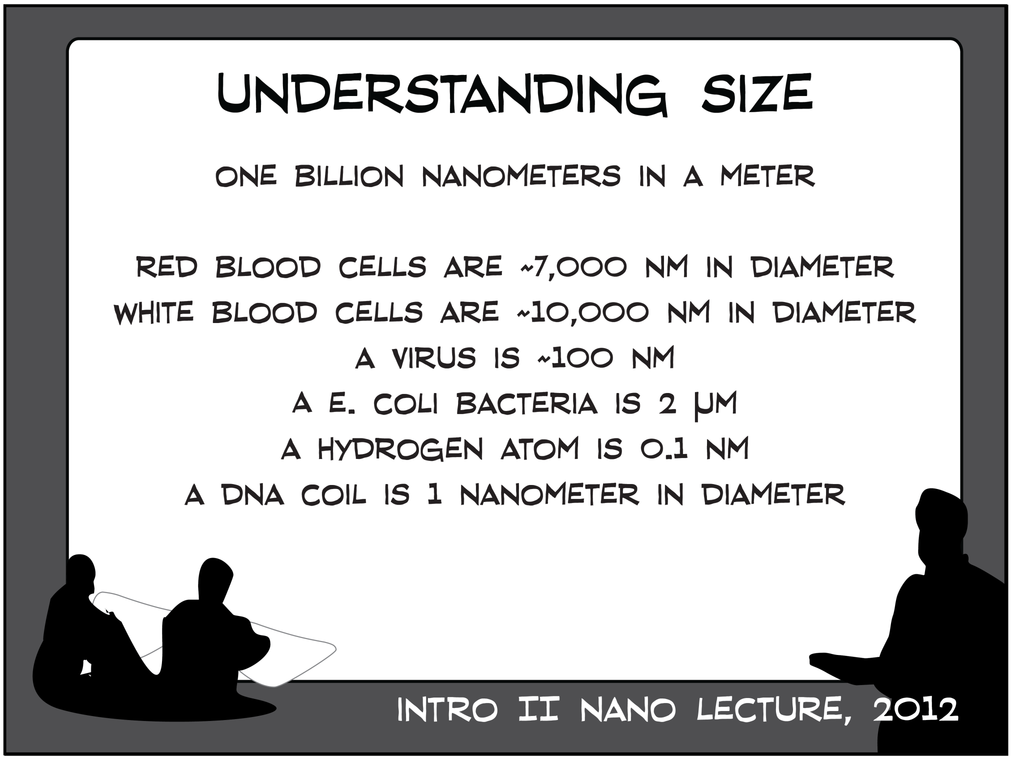

Illustration 6 Understanding size.

Nanoengineering builds on the disciplinary knowledges and practices of physics, chemistry, materials science, biology, and the engineering corollaries of these sciences, and therefore can be understood as continuous with these fields. Due to this, one might suspect that "nanoengineering" and "nanotechnology" are empty terms, buzzwords geared toward procuring enthusiasm and money, but nothing more. This may be partially correct, but it is not the whole story. This is because nanoengineering—now becoming institutionalized as a discipline—is not just a collection of preexisting practices haphazardly brought together under a unifying term. The practices of consolidating a discipline include institutional and technical elements—not surprisingly—but also political, moral, social, cultural, and material elements as well. Through the interaction of institutional structures, funding regimes, personal and professional histories and ideologies, instruments, popular culture and media, local and national cultures of innovation and technoscience, the affordances and constraints of material on the nanoscale, and the imperatives to educate and train a new generation of engineers to think and act as nanoengineers, nanoengineering comes to signify a particular mode of world-making that exceeds its constitutive technical practices and instruments.

Though what might constitute novelty in the realm of nanotechnologies may vary considerably, a robust engagement with the societal dimensions of nanoscale technologies should strategically assume that any technology that incorporates nanoscale materials or devices does so precisely because the nanoscale offers some novel attribute. I say this for two reasons. First, the interest in and justification of nanotechnology are based on the fact that materials exhibit unique properties and behaviors at the nanoscale due to quantum effects; nanoscale gold, for example, is materially different from "bulk"[6] scale gold.

6. Nanoengineers refer to "bulk" materials when distinguishing from nanoscale materials; bulk signifies that the material is at a micro or macro scale size which therefore means that its behaviors do not exhibit the peculiarities associated with quantum mechanics.

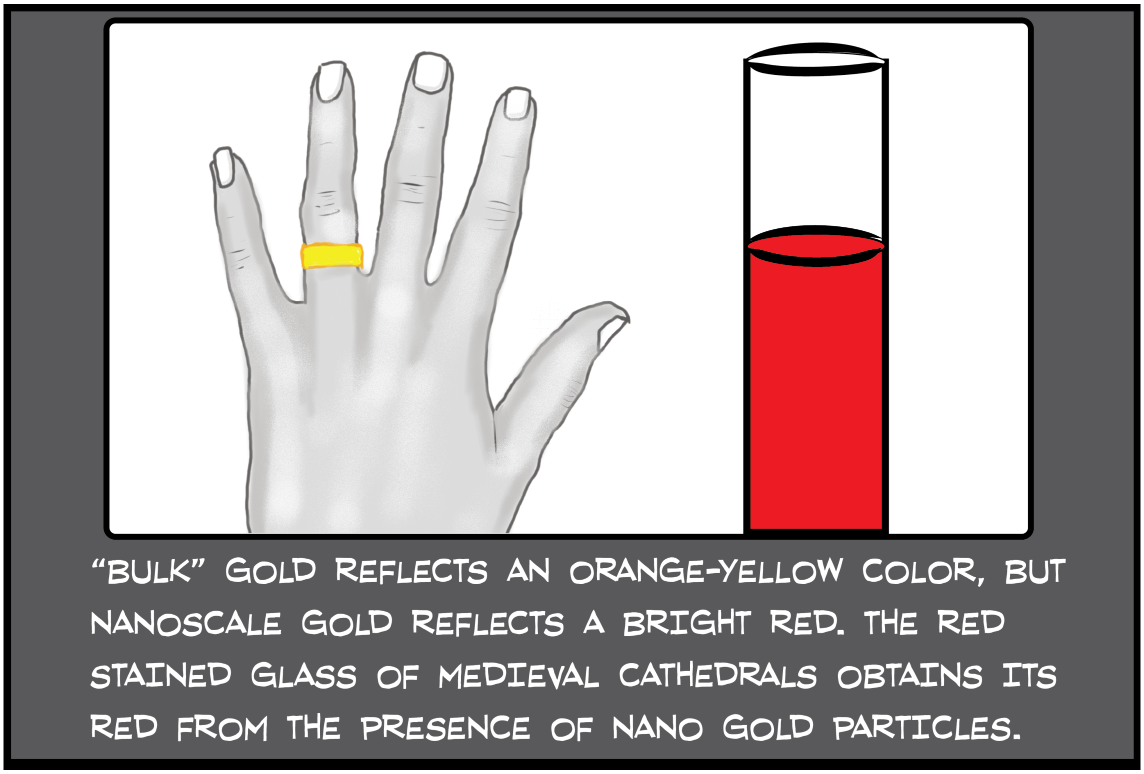

Illustration 7 Bulk gold and nano gold in solution.

While such differences and their consequences may vary across elements and assemblages, it is this change between microscale and nanoscale properties and behaviors that constitutes uncertainty and must be examined in its specificity for each nanotechnology application. Second, without an Office of Technology Assessment (OTA) and in an environment that is arguably anti-regulatory and pro-innovation, the political and economic pressures toward rapid research, development, and marketization of nanotechnologies are not matched by an equal financial or political commitment to interrogate the societal dimensions of these technologies.[7] There are currently over 2,000

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7. Although the National Nanotechnology Initiative (NNI) does support engagement in the ethical, legal, and social implication of nanotechnology (ELSI), its description of the purpose of such engagement ties it directly to commercialization: "Addressing ELSI in a proactive manner is critical to ensure public

nanotechnologies on the market that either identify themselves as containing nanoscale materials or that are highly likely to contain them, according the Project on Emerging Nanotechnologies at the Woodrow Wilson School.[8] These include sunscreens and cosmetics, antibacterial textiles and materials, pharmaceuticals, and foods.

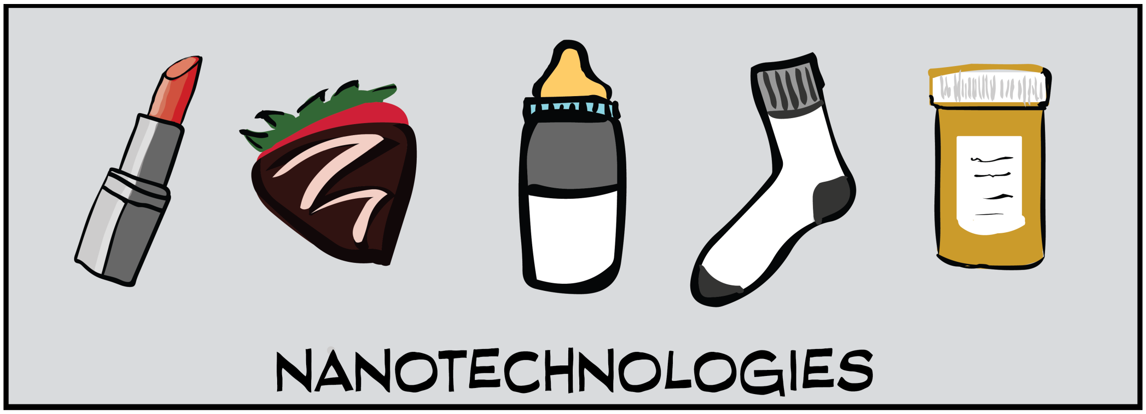

Illustration 8 Nanotechnologies. That is, conventional items that are now incorporating nanoscale materials.

There is also active research in a wide variety of domains, including energy and military applications, environmental remediation, and medical diagnostics and therapeutics. And an independent study by Lux Research reported that nano-enabled products generated $1 trillion worldwide in 2013.[9] Federal agencies like the Food and Drug Administration (FDA) and Environmental Protection Agency (EPA) are involved in evaluating the health

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trust in nanotechnology and to promote innovation and commercialization of NEPs." (http://www.nano.gov/you/ethical-legal-issues, accessed March 10, 2016). It does support two Centers for Nanotechnology & Society, one at Arizona State University and one at the University of California-Santa Barbara. The former received NSF funding of $12.7 million over ten years.

8. http://www.nanotechproject.org/. This number, constrained primarily to self-reporting, is conservative.

9. Cited by the NSF: http://www.nsf.gov/news/news_summ.jsp?org=NSF&cntn_id=130586&preview=false. Accessed on May 26, 2015.

and environmental implications of nanotechnologies. But rather than a precautionary approach that places the burden of proof on evidence of safety, nanoscale materials are largely presumed to be the same as their bulk counterparts, and therefore the burden of proof is on evidence that demonstrates they are different in ways that have negative health or environmental consequences:

> Because many regulatory agencies do not consider a nanotechnologically manufactured substance different from the conventional substance, the manufacture and use of nanotechnology products are currently not specifically regulated. Typically, nanosized substances are treated as variations of the technical material or existing formulation and thus do not require a separate registration. A main reason for producing a nanosize form of a registered substance, however, is that conversion of a substance to a nanoparticle imparts new properties to the substance (e.g., enhanced mechanical, electrical, optical, catalytic, biologic activity). Thus, as stated above, although the toxicology of the base material may be well defined, the toxicity of the nanosize form of the substance may be dramatically different from its parent form. As a result, new toxicology data on the nanosize form of a substance is likely to result in a different hazard assessment for the NPs.[10]

This presumption of safety in regulatory practices structurally positions research into the ethical, legal, social, and environmental dimensions of nanotechnology as temporally downstream from nanotechnology research and innovation. Therefore the regulatory structure is not well-positioned to intervene before the technology is blackboxed, when key insights about the broader implications of a particular technology may yet be incorporated into or intervene in a technology’s design.

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10. Günter Oberdörster, Eva Oberdörster, and Jan Oberdörster, “Nanotoxicology: An Emerging Discipline Evolving from Studies of Ultrafine Particles,” *Environmental Health Perspectives* 113, no. 7 (2005): 835.

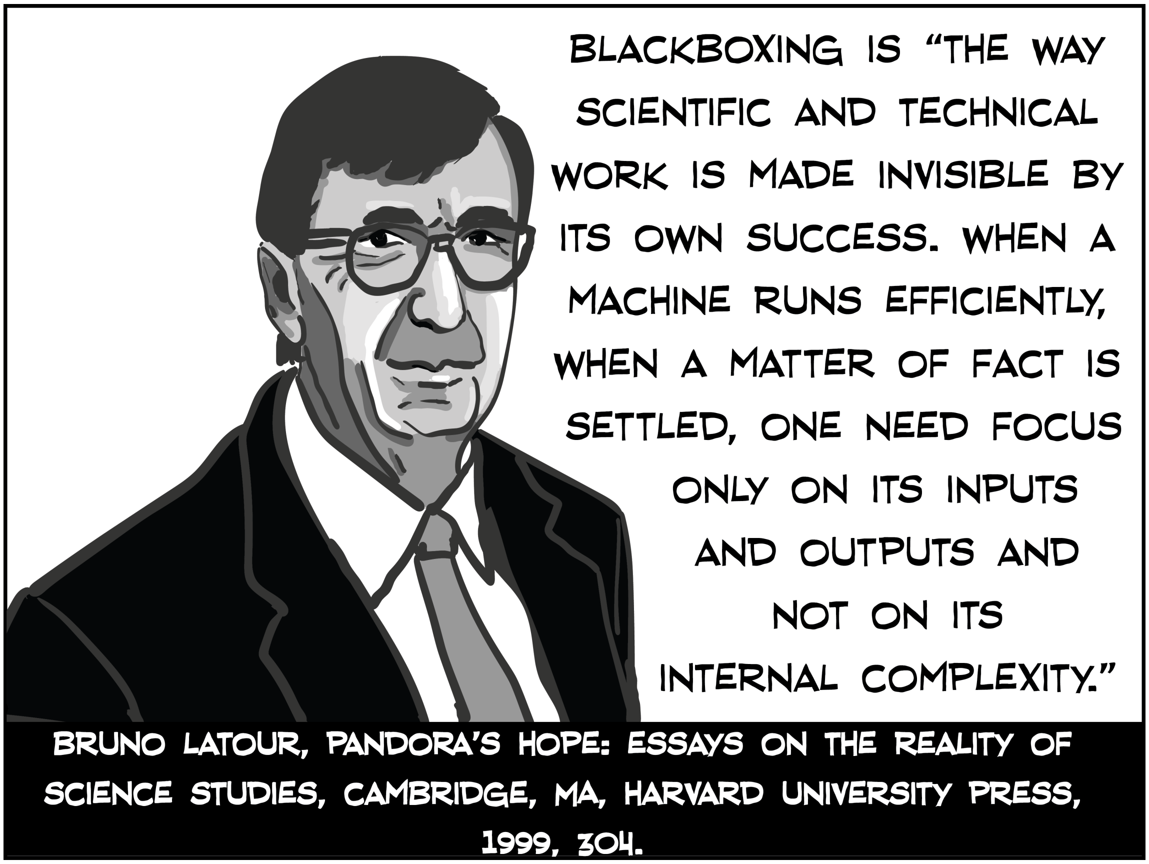

Illustration 9 Bruno Latour on blackboxing. Blackboxing is "the way scientific and technical work is made invisible by its own success. When a machine runs efficiently, when a matter of fact is settled, one need focus only on its inputs and outputs and not on its internal complexity."[11]

My own interest in nanotechnology specifically was inspired by a 2007 article in *OnEarth* by Robin Marantz Henig called "Our Silver-Coated Future," in which Henig explores the widespread uptake of nanosilver in consumer products, most commonly in products where it will come into direct contact with the human body (for example, in socks, baby bottles, food containers, and coatings on computer keyboards, to name a few). She writes that despite few studies on the safety of nanosilver, such an explosion of consumer products can occur because there are not any requirements for premarket safety

11. Bruno Latour, *Pandora's Hope : Essays on the Reality of Science Studies*, Cambridge, Mass.: Harvard University Press, 1999, 304.

testing.[12] Yet there is some uncertainty about the safety of nanoparticles in the human body and in the environment. She writes:

> One study of cells in culture, for instance, showed that when human lung tissue is exposed to carbon nanotubes, the lung cells see these not as foreign agents but as a biological substrate on which to build other tissue. Rather than mounting an immune response to attack the nanotubes as invaders, the lung cells start building layers of collagen around them…. Similar questions about the safety of nanoparticles arise from animal models showing that they can get into the bloodstream through the skin and then travel to vital organs, including the brain.[13]

She also writes about the possibility of bacterial resistance to nanosilver used as an antimicrobial, and the potential effects of nanosilver shedding from consumer products and making its way into the ocean, where it is potentially bioavailable and toxic.

To the extent that the government engages the societal dimensions of nanotechnologies, similar to the examples above, these dimensions are often narrowly defined in terms of health and environmental impacts, with broader constructions receiving limited attention despite an early interest in approaching nanotechnology with a strong ELSI component (Ethical, Legal, and Societal Implications). But there is the potential for nanotechnologies to raise ethical, legal, social and political questions that are not reducible to health or environmental impacts. For example, while MIT's Institute for Soldier Nanotechnologies frames its research in terms of solder protection,[14] it is reasonable to inquire about what kinds of military technologies might be enabled by such

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12. Robin Marantz Henig, "Our Silver-Coated Future," In *The Best American Science and Nature Writing 2008*, edited by M.D. Jerome Groopman, 119-32, Boston: Houghton Mifflin Company, 2008, 125.

13. Ibid., 125.

14. http://isnweb.mit.edu/, accessed March 11, 2016.

research, as well as how such technologies might be taken up in a domestic context. For example, can nano microphones be used for domestic surveillance, and with what consequences?

When the National Nanotechnology Initiative (NNI) was established by President Bill Clinton in 2000, there was a broad concern by nano enthusiasts that the public would approach nanotechnology with fear and would recapitulate the kinds of debates that emerged around genetically modified organisms in the 1990s.[15] The subsequent establishment of several national centers for engaging ELSI issues in nanotechnology and the requirement that nanotechnology research would incorporate some ELSI component in order to obtain funding anticipated public reticence and were in part, I would argue, an attempt to address it.[16] In the early 2000s especially, as nano was yet in an early phase of consolidation, there was concern that the making of Michael Crichton's novel *Prey* (2002) into a movie would result in the public being introduced to nano through the

15. Phillip J. Bond, "Preparing the Path for Nanotechnology" in *Nanotechnology: Societal Implications I*, edited by Mihail C. Roco and William Sims Bainbridge, National Science Foundation (U.S.), National Science and Technology Council (U.S.). Subcommittee on Nanoscale Science Engineering and Technology, and World Technology Evaluation Center, Dordrecht, The Netherlands: Springer, 2007. Take, for example, this statement delivered by Bond, a former Undersecretary for Technology at the U.S. Department of Commerce, at a workshop sponsored by the Nanoscale Science, Engineering, and Technology Subcommittee in 2003: "We also know from history that the body politic is susceptible to the virus of fear. When the public catches a public-policy cold virus, their elected representatives sneeze. Our democratic institutions are designed to be responsive to the public. To keep technology moving forward, we must prevent fear from taking hold among the public" (27).

16. George Whitesides and Paul Alivisatos, "Fundamental Scientific Issues for Nanotechnology" in *Nanotechnology Research Directions: IWGN Workshop Report Vision For Nanotechnology R&D in the Next Decade*, National Science and Technology Council Committee on Technology Interagency Working Group on Nanoscience, Engineering and Technology (IWGN). Such concerns are often expressed in the late 1990s and early 2000s. For example, in the 1999 report recommending the creation of the National Nanotechnology Initiative, Whitesides and Alivisatos write in a list of priorities, "Address the problems of public perception of threats from nanoscience with active programs to reduce any possible threats and educate the public" (9). Subsequent creation of NSF Centers for Nanotechnology in Society (at the University of California-Santa Barbara, for example) can be seen as attempting to both reduce possible threats and educate the public.

apocalyptic vision of "grey goo." In the novel, a secret Pentagon project using molecular assembly to develop nanorobotic weaponry goes awry when the nanobots evolve into intelligent swarms that can take over and mimic humans.[17] For reasons that are not clear, the movie was not in fact made.

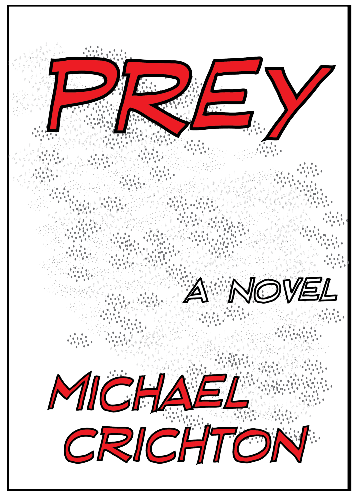

Illustration 10 Michael Crichton's novel *Prey* came out in 2002.

In the meantime, popular nano-related journalism has been overwhelmingly positive. Nanotechnology has become more established as an industry with applications in a wide variety of domains that are now commercially available. Nanotechnology is thereby becoming less vulnerable to public challenge.[18]

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17. Diana Bowman, Graeme A. Hodge, and Peter Binks, "Are We Really the Prey? Nanotechnology as Science and Science Fiction," *Bulletin of Science, Technology & Society* 27, no. 6, December 1, 2007, 435-45. See Bowman, Hodge, and Brinks for an interesting analysis of how *Prey* can be read as a regulatory story.

18. Bruce Lewenstein, Jason Gorss, and Joanna Radin, "The Salience of Small: Nanotechnology Coverage in the American Press, 1986-2004," in *International Communication Association*, 1-39, 2005. In an analysis of U.S. media coverage of nanotechnology from 1984-2005. Lewenstein, Gorss, and Radin write that, "As with biotechnology, coverage of nanotechnology throughout this period is overwhelmingly positive, focusing on progress and potential economic benefits, and with little discussion of attendant risks. Nanotechnology coverage does, however, focus more on risks from the outset than biotechnology did, suggesting that issues of public accountability are growing more salient to journalists."

It is in this context that I come to the questions that underlie this dissertation, which are not focused on public perception but rather on what kind of project nanoengineering is. How is the 21st century consolidation of nanoengineering as a discipline articulated with and through particular assumptions and ideologies: first, about science, innovation, and economics, including the proper roles of the university, the state, and industry; second, about what constitutes and what should constitute public and private; and third, about democracy, the citizen, and the good? How do nanotechnologists themselves engage with questions about the societal dimensions of nano, and how do they understand the ways that the macroscale world shapes and is being shaped by their nanoscale manipulations? How are ethics and politics articulated (or not) in this latest iteration of technoscience? What visions of the future motivate nanoengineers' work, how do these futures come to be imagined, and how do nanoengineers see their role in making these futures? In sum, what imaginaries are at work in the emergence and disciplinary formation of nanoengineering?[19]

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19. Lucy Suchman, *Human-Machine Reconfigurations : Plans and Situated Actions*, 2nd ed, Cambridge ; New York: Cambridge University Press, 2007. I follow Suchman's succinct definition of the term "imaginary," which builds on feminist articulations of the term: "The word imaginary…shares with the more colloquial term imagination an evocation of both vision and fantasy. In addition, however, it references the ways in which how we see and what we imagine the world to be is shaped not only by our individual experiences but also by the specific cultural and historical resources that the world makes available to us, based on our particular location within it. And perhaps most importantly…cultural imaginaries are realized in material ways. My inspiration for this approach is Haraway's commitment to what she names "materialized refiguration…" (1).

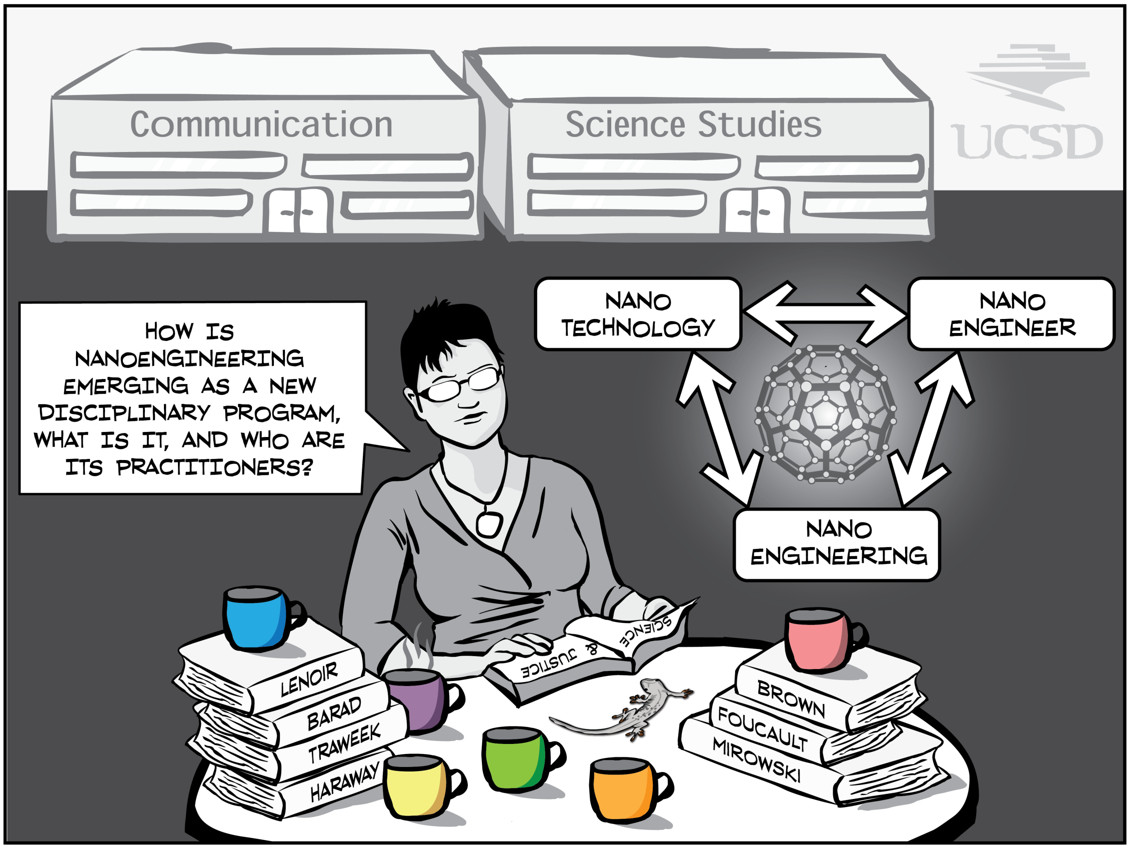

Illustration 11 Beginning an ethnography in 2010. I started with the broad question: How is nanoengineering emerging as a new disciplinary program, what is it, and who are its practitioners?

To address these questions, I have engaged in an ethnographic research project examining a new department of nanoengineering and its undergraduate nanoengineering major. My site is the Department of NanoEngineering, which was established at the University of California-San Diego (UCSD) in 2007. This is the first department of nanoengineering in the world, or the second if you count the Colleges of Nanoscale Science and Engineering (CNSE) at SUNY Polytechnic Institute in Albany, New York, accredited in 2004.[20] UCSD's department began to offer an undergraduate

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20. http://www.sunycnse.com/Home.aspx. The reason I put it this way is because my site counts itself as the first department.

nanoengineering major in the Fall of 2010, again second to the CNSE's and one of only a handful of such programs in the world.[21] Even as some continue to doubt whether nanoengineering is or should be understood as a distinct discipline,[22] in this site the faculty, administrators, and students are deeply invested in establishing nanoengineering as a distinct discipline. In the context of educating undergraduate students particularly, nanoengineering faculty have to be quite explicit about how they are defining the field. That is, they must answer the question of what nanoengineering is and what it means to be a nanoengineer, and they do so in their lectures and in their research practices.

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21. Though there are an increasing number of Ph.D., M.S., and certificate programs or designated emphases, there are still not many programs for comprehensive undergraduate degrees. The National Nanotechnology Initiative maintains a list of programs here: http://www.nano.gov/education-training/university-college.

22. Patrick Lin and Fritz Allhoff, "Nanoscience and Nanoethics: Defining the Disciplines," Chap. 1 in *Nanoethics : The Ethical and Social Implications of Nanotechnology*, edited by Fritz Allhoff, Patrick Lin, James Moor and John Weckert, 3-16, Hoboken, N.J.: Wiley-Interscience, 2007. See Lin and Allhoff for a brief discussion of the ontological status of nanotechnology as a distinct discipline.

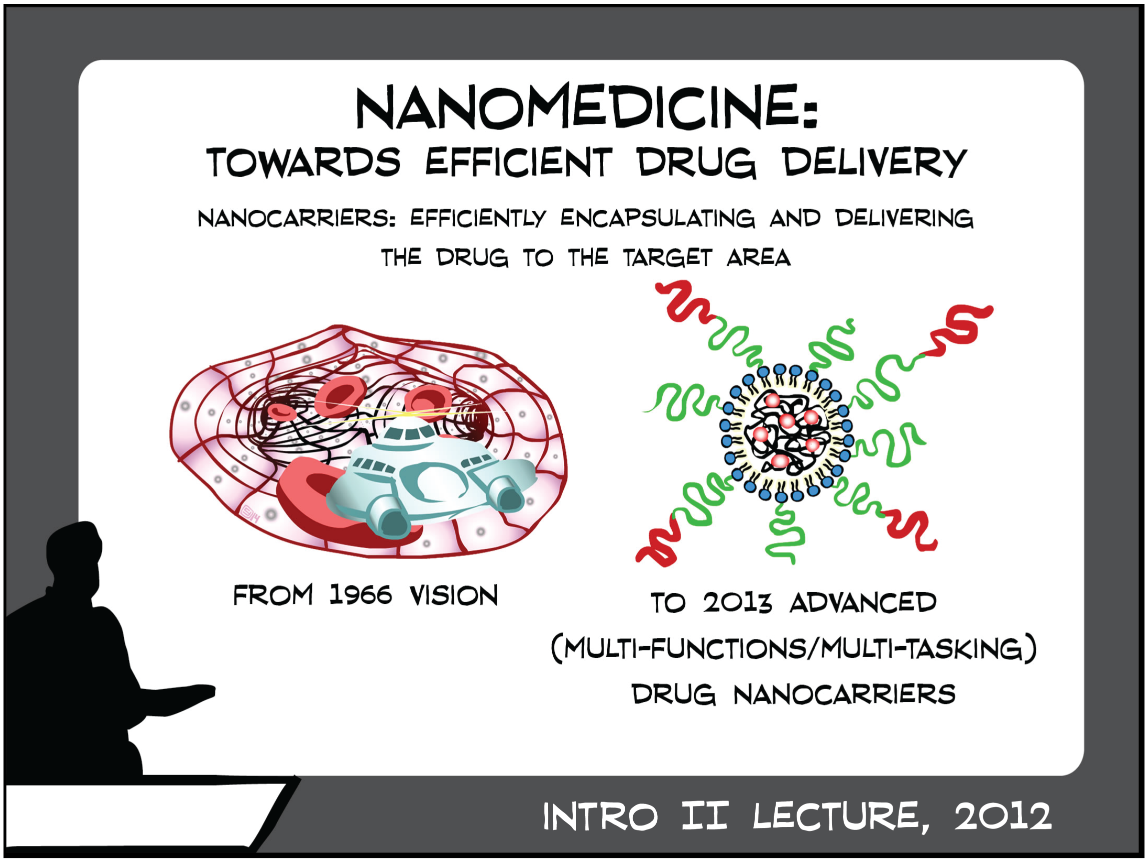

Illustration 12 Nanomedicine. In this introductory nanoengineering lecture, the professor defines nanomedicine in part by drawing a parallel to the 1966 science fiction film *Fantastic Voyage.*

This is therefore an ideal site for looking at how a new disciplinary and professional identity is being established, how an ethos and worldview are coproduced with technoscientific practice, and how science and innovation are being done in the 21st century American university.

With concerns about whose visions of the future come to matter; how science can be done ethically, sustainably, and democratically; and the roles of scientists in science and technology policy, I consider the ways in which nanoengineering comes to be institutionalized as an intrinsically ethical practice and identity. I argue that the "nano world," the nanoengineer, and nanoengineering as an institutional and disciplinary formation are co-produced. In this co-production, the highly technical practices of manipulating invisible matter are intimately linked to a knowledge- and world-making ethos that understands nano and the nanoengineer as enacting the good on several levels: first, by identifying Nature as the first nanotechnologist and framing nano as natural; second, by situating nanotechnology within a narrative of universal progress that will benefit humanity; and third, by generating economic activity through innovation, which is itself understood as socially beneficial in that innovation is understood as producing jobs and as expanding consumer choice. This ethos undergirds an explicitly entrepreneurial scientist-engineer identity that pursues a promissory vision of innovation for the benefit of society. Universal assumptions about progress, humanity, benefit, and the future are imbricated in the definitions, goals, and practices of nanoengineering. With funding sources that demand quick economic benefit and a political economy that relies on the market to define, justify, and deliver nanotechnologies worthy of research and development, the nanoengineer's professional vision sees market opportunities and benefits for humanity as at least mutually dependent if not synonymous. In this context, the ethical and social implications of nanotechnology are narrowly understood in terms of environmental toxicity, and—in my research site—even nanotoxicology is deemed a separate field that is only peripherally introduced in the context of an undergraduate nanoengineering curriculum.

Methods

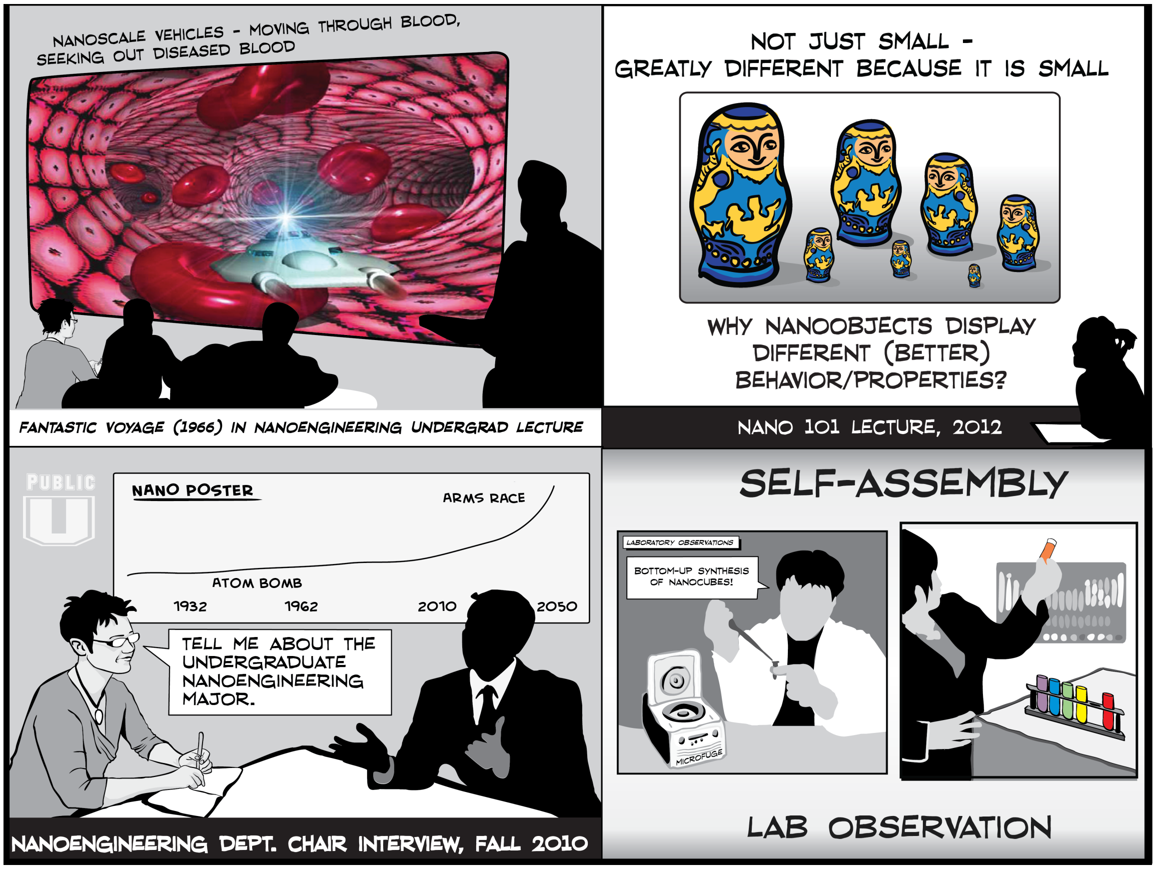

Illustration 13 Methods. My methods have included conducting interviews with faculty, students and administrators; observing undergraduate courses; observing a nanoengineering laboratory; analyzing the media used in the department and curriculum, and attending and observing department events.

Beginning with my observation of the very first undergraduate class offered in the Fall of 2010, I have subsequently observed most of the required undergraduate courses, some more than once. In these courses I took audio recordings of the lectures and paid particular attention to the lecture slides and the media and texts used in the courses. In many cases, the instructor granted me permission to the course website when one was used, which allowed me access to the lecture slides and the professor’s communications with the class.[23] This material was very useful for examining how popular culture gets enrolled in technical education and in the production of a discipline, how the faculty articulate a disciplinary history, and how the faculty explicitly and often implicitly communicate an ethos, worldview, and professional identity in the classroom.

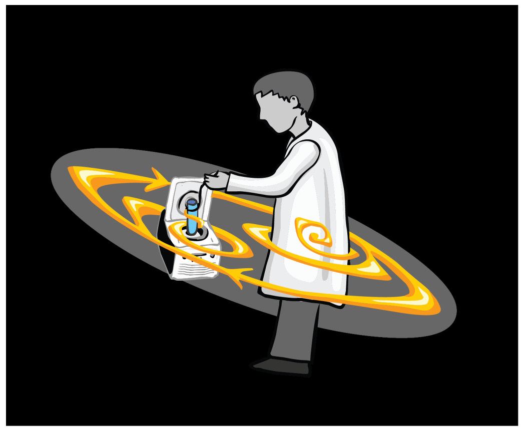

Illustration 14 Nanoengineer in the laboratory.

Additionally, for one and a half years I conducted weekly observations of a nanoengineering laboratory and attended its weekly lab meeting.[24] Here I primarily focused on a few undergraduate students in the laboratory, though my observations included their interactions with graduate students, a postdoctoral researcher, and the faculty principal investigator (PI). Additionally, the entire group participated in the weekly laboratory meeting. Laboratory observation allowed me to get a better

23. For all course observations, I obtained written permission from the professor and verbal permission from the students.

24. This particular lab was recommended to me by the chair of the department because it is small. During most of my observations, only a couple of people were present at any given time. Some labs are quite large, with many students, postdoctoral research fellows, and visiting researchers. From discussions with students who had participated in such labs, I understand that the culture can be quite different from what I observed. One laboratory was described to me as a “publication mill” with rapid turnaround of research results, intense competition, and strong emphasis on innovating products to market. My lab by contrast was quiet, seemingly relaxed, with attention on more theoretical problems as well as application goals.

understanding of nanoengineering research practices, and, due to the nature of the lab I was observing, to get a better understanding of the practices of self-assembly (a nanomanufacturing technique). I rarely used audio recording in the laboratory and never in the lab meetings as I was attentive to the fact that this was a space of intellectual and in some cases proprietary development that might be sensitive. Yet in the laboratory I was able to attend to situated and embodied ways of knowing the nanoscale. Nanoparticles may be invisible, but in the lab nanoengineers come to know the nanoscale through precisely measuring and carefully combining solutions according to recipes, developing an embodied sense of how to handle nanomaterials (such as how to forcefully add solution through a pipette or lightly tap out a powdered substance onto a scale), calculating scalar conversions, handling glass vials containing nanoparticle solutions, putting those vials into sonicators and then timing and evaluating the resulting changes by examining consistency and color, and, in short, developing the know-how that renders the invisible visible and knowable through traces and indices. Additionally, in the weekly lab meeting I observed the interconnections between pedagogy and research, between disciplinary and professional development, between problem solving and research trajectories, and between intellectual curiosity and political economic factors in these trajectories.

From 2010 through 2014, I conducted eighty-five interviews with students, faculty, and administrators. I attempted to ask for interviews with all nanoengineering students taking the courses I was observing, and the resulting interviews were with those students who agreed to an interview. With approximately ten students I was able to follow up with an interview each year during their four-year trajectory from freshman to graduating senior. I asked for interviews with almost all of the faculty, including any who taught the classes I observed, and was able to do at least one short interview with most of the faculty who were teaching courses between 2010 and 2014. I also interviewed the dean of the Jacobs School of Engineering, whom I'd observed welcoming incoming nanoengineering students two years in a row at a university event in the spring that welcomes accepted students. Most interviews were 30-45 minutes and in all cases they were semi-structured. Faculty and administrator interviews gave me insights into faculty perspectives on what constitutes nanoengineering, how they understand responsibility and ethics in nanoengineering and in nanoengineering education, how they approach innovation, and what they are doing in their own research.

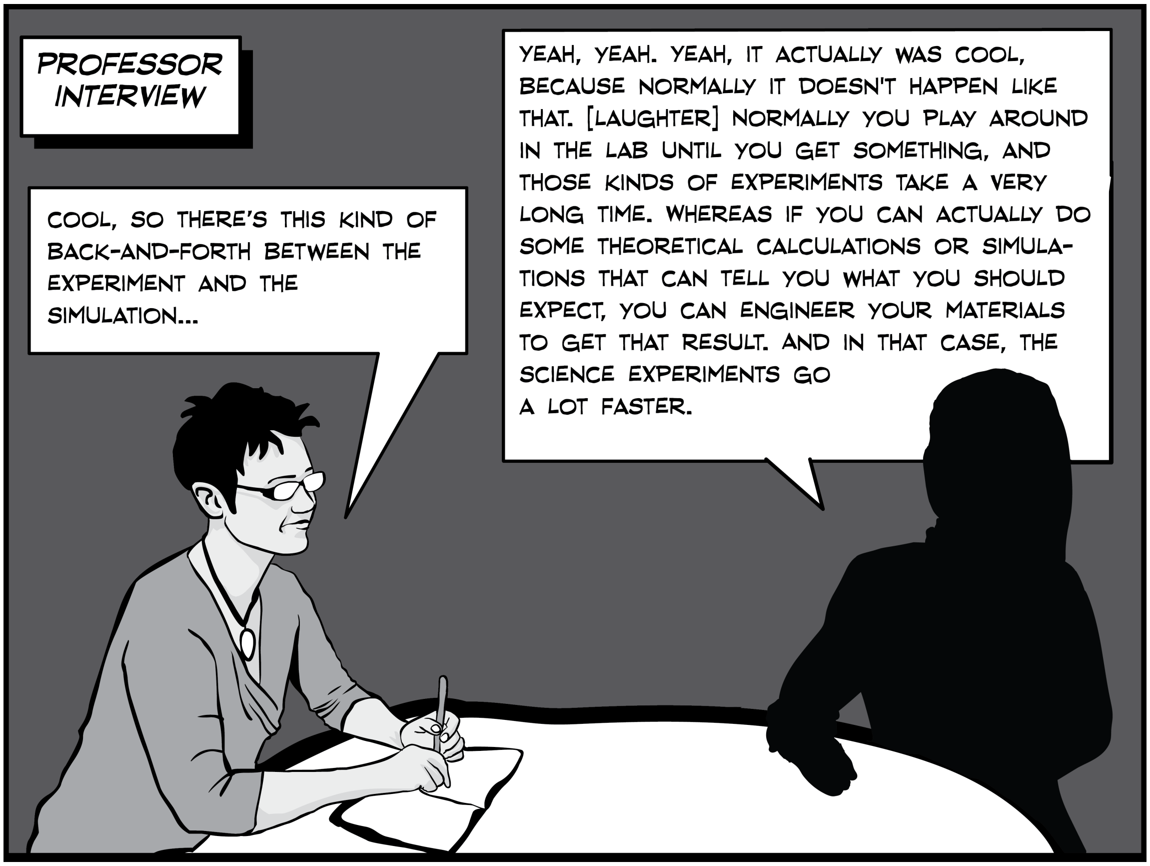

Illustration 15 Faculty interview. "Normally you play around in the lab until you get something, and those kinds of experiments take a very long time. Whereas if you can actually do some theoretical calculations or simulations that can tell you what you should expect, you can engineer your materials to get that result. And in that case, the science experiments go a lot faster."[25]

Student interviews helped me to assess their developing understandings of nanoengineering and their relationships to it, what visions of the future they embraced and that motivated them, what challenges they experienced in the major, how they understood their career possibilities in industry and academia, and how they understood the societal dimensions of nanotechnologies.

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25. Interview with NanoEngineering professor, November 14, 2014. Transcribed by author.

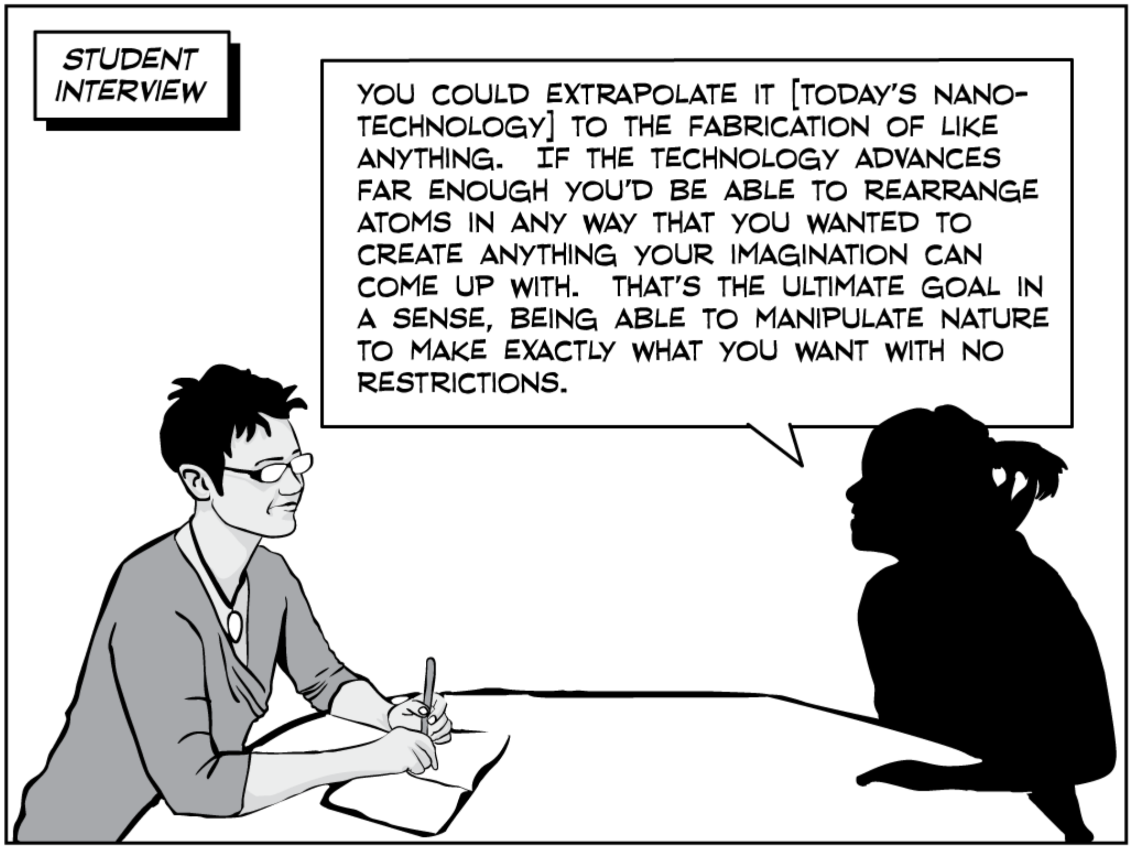

Illustration 16 Student interview.

They were particularly helpful for learning whether and to what extent they heard the same things I heard when I observed course lectures, and for asking them to speak more about certain topics covered in class. In terms of the ten students I interviewed each year, I am not inclined to make strong claims about how their views changed over four years with such a small sample. However the aggregate data suggest that while students' technical understandings of nanoscale engineering deepens, their perspectives on the social and ethical dimensions of nanotechnology and on their role in envisioning and making futures perhaps changes less.

Through a close analysis of the media and texts used in the curriculum and in the department more generally, I was able to examine the ways in which nanoengineering is figured in this site through imaginaries that engage popular culture, entrepreneurial and innovation cultures, and western technoscientific traditions.

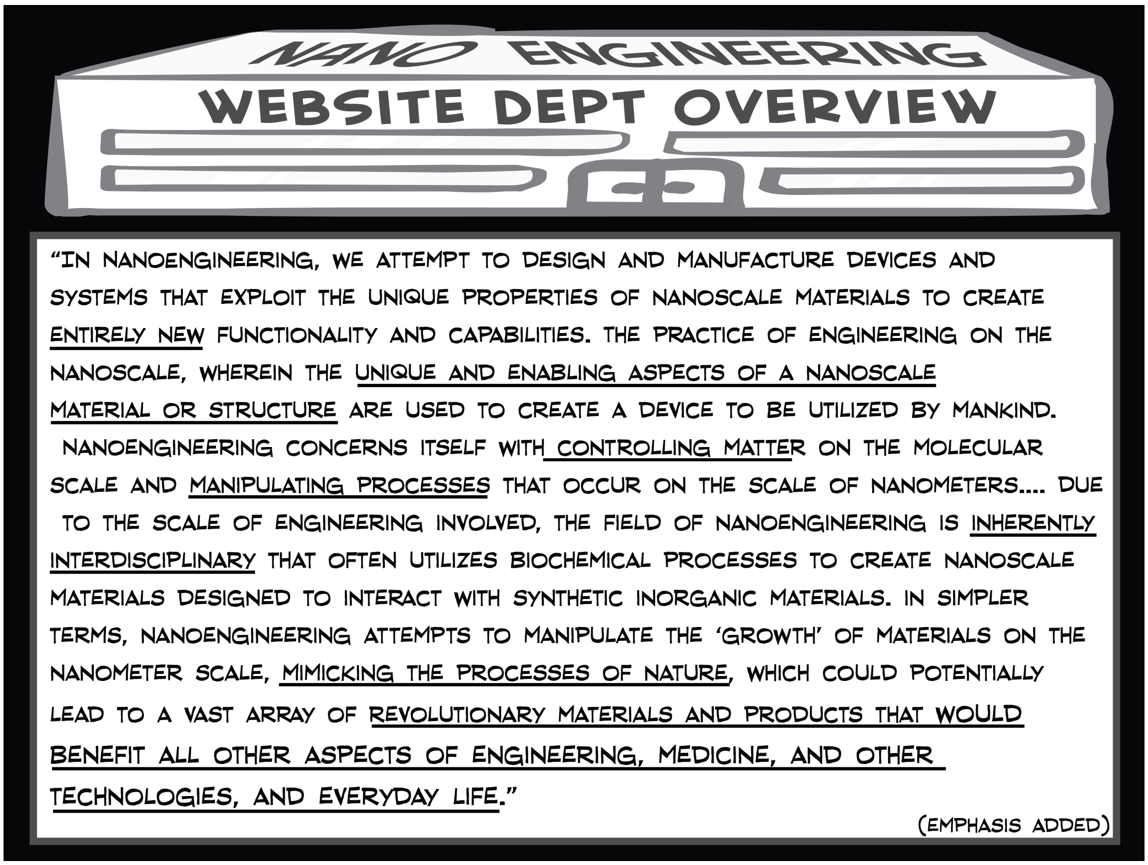

Illustration 17 Department overview.[26]

I additionally attended department events, including student-led events, and a department faculty meeting. Finally, for one year I collaborated with the chair of the department and the faculty and graduate students to redesign and rewrite the department newsletter. Based on interviews with faculty PIs, I wrote short articles for the newsletter.

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26. NanoEngineering Department, "Department Overview," accessed December 3, 2015, http://nanoengineering.ucsd.edu/about-us/overview.

Unfortunately, this newsletter has not yet made it to production for reasons outside my control.[27] Nevertheless, conducting the interviews, writing the articles, and receiving revised versions and images from faculty PIs and their graduate students were helpful activities for understanding how the nanoengineers wished to represent their research and department, how they professionalized their verbal communications for written form, what they felt was important about their work and what they hoped to achieve.

Theoretical Approach and Contribution

Theoretically and methodologically, I have approached this project from perspectives grounded in feminist science studies, traditional science and technology studies (STS), and communication. Attending to the communicative dimensions of technoscientific practice, including embodied interaction, media, and discourse, I recognize communication as fundamental to technoscientific practices even as I attend to the material practices of knowledge production so central to STS. The discursive and material aspects of knowledge production come together nicely in feminist science studies, which has long seen them as inseparable and as historically bound up in western, imperial, and patriarchal structures that have enacted politics under the guise of objectivity.[28] I employ a standpoint methodology[29], studying up in terms of selecting a site

27. For some time, the newsletter appeared to be on hold awaiting the chair's welcome letter. Eventually, I provided the department with all original files so that they could publish it without my assistance. Since then, there is a new department chair and it is not clear if there is continued interest in publishing an updated newsletter.

28. See, for example, Donna Haraway, "Situated Knowledges: The Science Question in Feminism and the Privilege of Partial Perspective," *Feminist Studies* 14, no. 3 (1988): 575-99.; Donna Haraway, *Primate Visions: Gender, Race, and Nature in the World of Modern Science*, New York: Routledge, 1989; Valerie Hartouni, *Cultural Conceptions: On Reproductive Technologies and the Remaking of Life*, Minneapolis: University of Minnesota Press, 1997; Evelyn Fox Keller, "The Gender/Science System or, Is

of geographical and disciplinary privilege. Standpoint theory starts from the assumption that the activities of those in social and institutional positions of power limit what those in such positions can know and understand about themselves and the world, and that privileging the position of those at the bottom of social hierarchies as an epistemological strategy makes visible human relations and the attendant power dynamics at work in those relations.[30] By selecting a department of nanoengineering at a prestigious university in the United States, I am focusing my gaze on a site where the participants are in relative positions of power.

Sex to Gender as Nature Is to Science?" in *The Science Studies Reader*, edited by Mario Biagioli, xviii, 590 p. New York: Routledge, 1999; Helen Longino, *Science as Social Knowledge: Values and Objectivity in Scientific Inquiry*, Princeton, N.J.: Princeton University Press, 1990; Sharon Traweek, *Beamtimes and Lifetimes: The World of High Energy Physicists*, Cambridge, Mass.: Harvard University Press, 1988.

29 Standpoint theory emerged in socialist feminist thought in the 1970s. Looking to Marxist methodology that privileged the epistemic value of the proletariat, people like Dorothy Smith, Nancy Hartsock, Hilary Rose, and Patricia Hill Collins sought to privilege women and other people who benefitted least from the dominant framework of any particular discipline, practice, or 'problem' area (http://www.iep.utm.edu/fem-stan/#H8, accessed December 6, 2015). For articulations of standpoint theory and the practice of "studying up" see Sandra Harding, "Rethinking Standpoint Epistemology: What Is "Strong Objectivity"?" in *Feminist Epistemologies*, edited by Linda Alcoff and Elizabeth Potter, vii, New York: Routledge, 1993; and Sandra Harding, "A Socially Relevant Philosophy of Science? Resources from Standpoint Theory's Controversiality." *Hypatia* 19, no. 1 (2004): 25-47.

30. Sandra Harding, "Rethinking Standpoint Epistemology," 54.

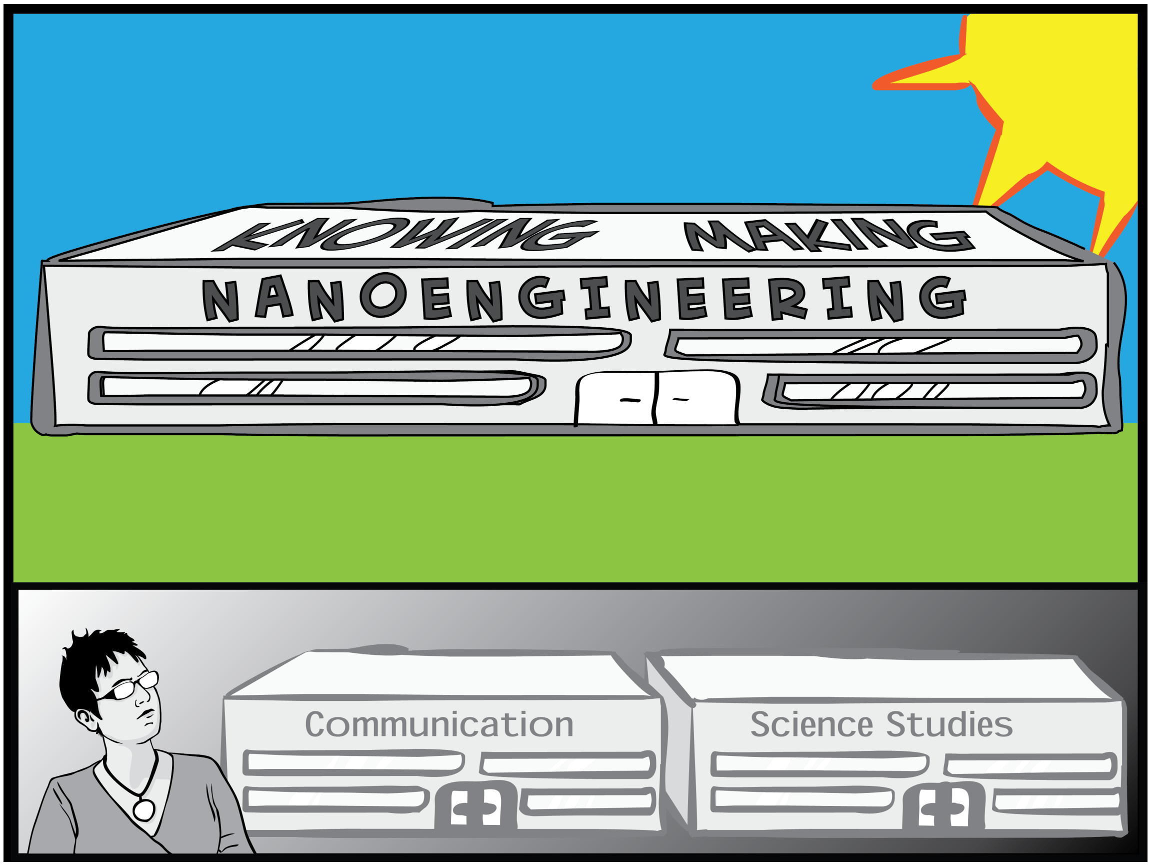

Illustration 18 My standpoint.

I particularly attend to the boundary drawing practices through which relevance and irrelevance are determined, through which traditional binaries—particularly nature and culture, and human and nonhuman—are reproduced in this disciplinary formation, and to who and what are excluded in the production and presumed beneficiaries of nano.[31]

This work contributes to the cultural studies of science and technology in the following ways. To feminist science studies, I provide two methodological contributions.

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31. Haraway, *Primate Visions*, 1989; Karen Barad, *Meeting the Universe Halfway: Quantum Physics and the Entanglement of Matter and Meaning*, Durham: Duke University Press, 2007. See Haraway for a discussion of the politics of boundary drawing practices, and Barad for her elaboration of boundary drawing as central to the apparatuses of knowledge production.

First, I experiment with multi-modality—specifically mixing prose and graphic-novel style illustration—to situate my knowledge production and practice reflexivity in my story-telling practices.

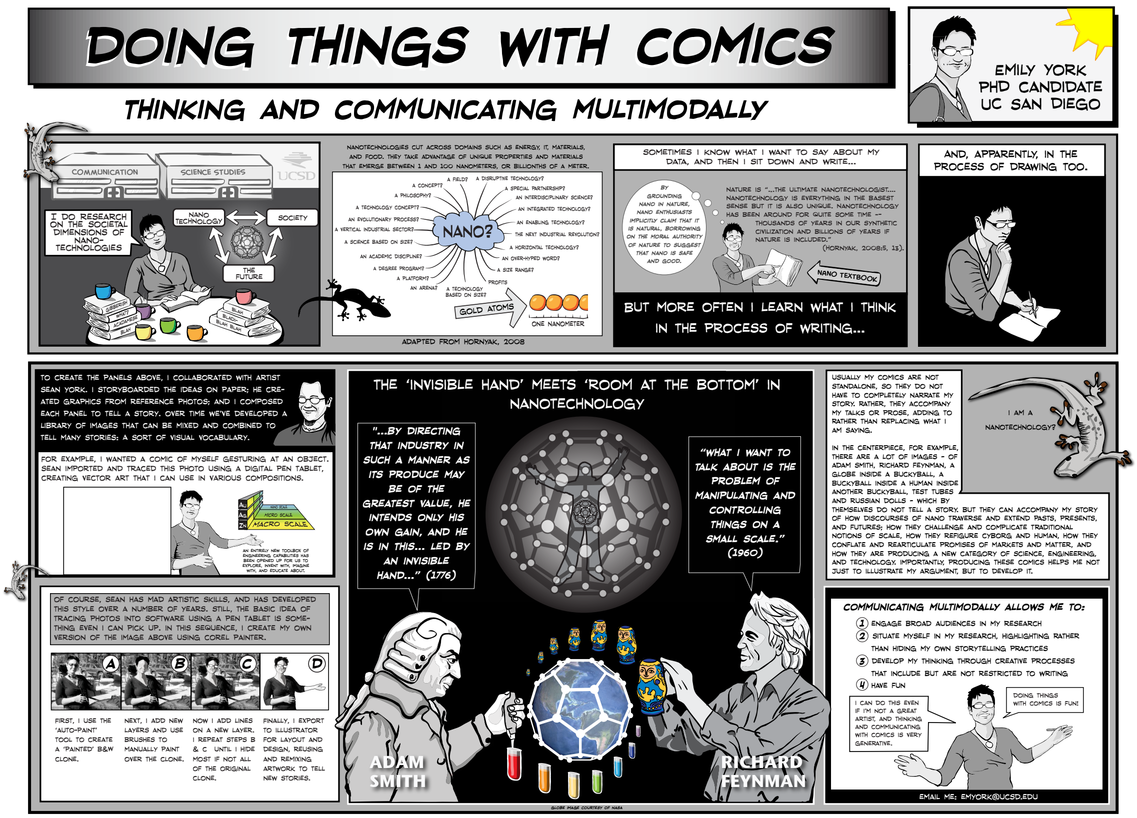

Illustration 19 Thinking and communicating multimodally.

There are three key feminist ideas that inform this: first, the idea that knowledge is situated;[32] second, that science (or knowledge production) is a kind of storytelling;[33] and third, that representation does not sit on top of or follow reality, but is rather inextricably part of the making-doing that constitutes matter and meaning and that enacts what is

32. Haraway, *Situated Knowledges*, 1988.

33. Haraway, *Primate Visions*, 1989; Traweek, *Beamtimes and Lifetimes*, 1988.

real.[34] I attempt to be responsible to my ethnographic observations and to the data I have gathered by acknowledging the constitutive role I play in producing that data. Therefore, comics—even more than photographs, perhaps—remind my audience and me that the question is not about representation *of* but about responsibility *to*—responsibility to that which I am producing knowledge about, to whom and what I am producing this knowledge for, and to the ways that my knowledge production is also part of making the world. These illustrations are the product of a collaboration between myself and an artist, Sean York.[35] Including anything that is part of a collaboration is risky in an academic world that rewards individual contribution, particularly as a junior scholar. But as a feminist scholar, engaging in collaboration as part of this multimodal communication is also a political act that challenges the competition and individualism of traditional academia. Second, I show how ethnography can be used to locate possibilities for political work—specifically, in this case, political work in the form of incorporating feminist pedagogies into the science classroom.

My key contributions to STS are threefold. First, I focus on the higher-ed science classroom as a key site for understanding the politics and ethics of knowledge production, and one that has been understudied in STS literatures. STS is known for going into the laboratory to show how knowledge is made and to show how the social is an intimate part

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34. Barad, *Meeting the Universe*, 2007; Haraway, *Primate Visions*, 1989.

35. During the early phrase of this project, I would sketch out illustrations with a pencil, and Sean would draw digital comics based on those illustrations. Together, we created a large library of objects that I use and reuse to tell different stories, configuring them into different arrangements to do so. By the end of this project, I had learned how to draw digital comics myself, and now I do most of the artwork myself. I draw artwork in Adobe Animate using a Wacom tablet and pen, then import that artwork into Adobe Illustrator to lay it out, add text, and do additional artwork to finalize a comic image.

of this production.[36] The classroom, however, is also an important site where scientists produce knowledge about knowledge production, articulating what counts as scientific knowledge, how scientific knowledge should be produced, who and what it is for, and what it means to be a scientist. In all of these categories, scientists participate in the production of a disciplinary and professional identity—and the values, ethos, and worldview that are part of this identity—which carries into the lab and workplace. Additionally, I regard the laboratory as another site of pedagogy. The social materializes in the lab not only in the objects of knowledge production, but in its subjects, and in the interconnections between the production of subjects and objects in the lab. Second, I contribute a case study of disciplinary formation that is significant because it is the first such study of nanoengineering. It examines such institutionalization in the making, and therefore as an ongoing process of consolidation that has not yet become blackboxed. Moreover, disciplinary formation is an area too that has received less attention than it might in STS. STS is focused on knowledge production, but the formation of a discipline cannot be separated from the knowledge-making practices that are produced within the discipline or those that are constitutively excluded as not part of the discipline. Disciplinary formation is therefore key to understanding knowledge production that takes place in and as part of a discipline. It is also a case study that is significant for thinking

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36 Bruno Latour and Steve Woolgar, *Laboratory Life: The Construction of Scientific Facts*, Princeton, N.J.: Princeton University Press, 1986. One of the early, canonical laboratory studies in the field is *Laboratory Life* by Latour and Woolgar.

Karin Knorr Cetina, "7 Laboratory Studies: The Cultural Approach to the Study of Science," In *Handbook of Science and Technology Studies*, edited by Sheila Jasanoff and Society for Social Studies of Science, 140-67, Thousand Oaks, Calif.: Sage Publications, 1995. For an overview of laboratory studies, see Knorr Cetina's “7 Laboratory Studies.”

through the role of the university in the political economy of contemporary technoscience, and demonstrating the ways in which the ideologies and practices of innovation economics are built into the pedagogies, disciplinary formations, and research practices of the university. Third, I contribute a communication perspective to STS analyses, showing how the communicative dimensions of pedagogy and practice—including practices of pointing, highlighting, and framing[37]—are productive of the values that are always present in science's material and discursive practices.

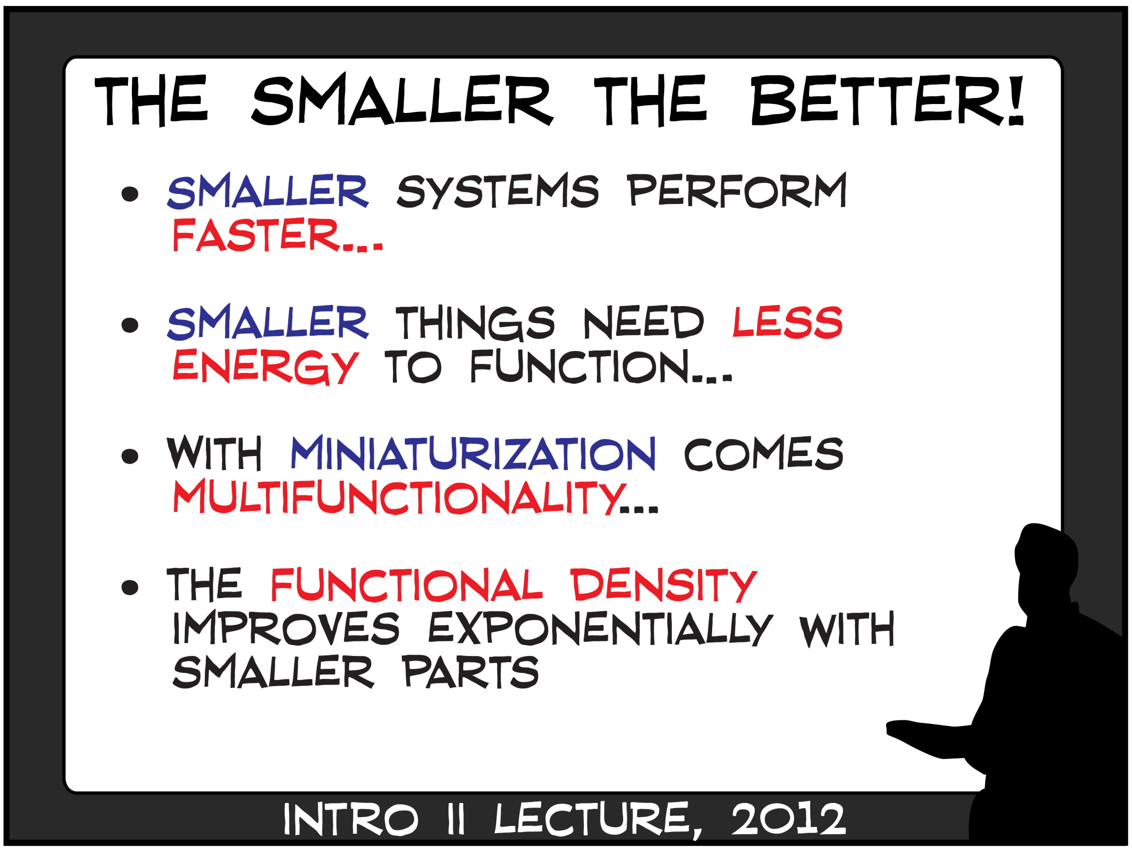

Illustration 20 Lecture slide with highlighting.

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37. See Goodwin, *Professional Vision*, 1994, for a discussion of how practices like pointing, highlighting, and framing produce a professional vision.

To the field of communication, I contribute an analysis of science communication that focuses less on that between insiders and outsiders as on that between insiders and soon-to-be insiders (undergraduate students). Examining the dynamics of communication in the classroom, I show how verbal and visual communication strategies are key to the transformation of a student into a nanoengineer. Moreover, I emphasize—particularly through my visual representations—that science communication within a disciplinary program is a material and discursive practice that is productive of the imaginaries and identities that constitute the disciplinary program. I additionally show how popular culture is figured into these imaginaries. Popular culture links the laboratory to the world outside the lab, inviting students into the practices of nanoengineering while reassuring them of their connection and commitment to the world outside of it. The fluidity of popular culture fantasies that traverse macroworld and nano world, and science fiction and everyday laboratory practice, works to enshrine the technical and mundane inside the excitement, hopes, and aspirations of realizing fantastic dreams.[38]

To the societal dimensions of emerging technologies, my case study is very uniquely positioned. While there is a growing literature on nanotechnology, there is little to be found on the institutionalization of nanoengineering, partially because such institutionalization is relatively new. Cyrus Mody has contributed some historical research on the role of instrumental communities in the emergence of nanoengineering,[39]

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38 See Milburn, *Nanovision*, 2008, for a discussion a discussion of science fiction in relation to nanotechnology.

39. Cyrus Mody, *Instrumental Community: Probe Microscopy and the Path to Nanotechnology*. Cambridge, Mass.: MIT Press, 2011.

and Ana Viseu has done an ethnography of a nanotechnology lab.[40] Others have done ethnographies of research practices in sites that include national research centers. Yet none have examined the disciplinary formation of nanoengineering. My site is one of the first and only departments of nanoengineering, and one of the first and only undergraduate majors, making this ethnography somewhat unique in its perspective. What I can contribute then is an empirical analysis of how the societal dimensions of nanotechnologies are (or are not) engaged in the undergraduate classroom; how ethical, legal, and societal implications do or do not figure into the practices of research and pedagogy in this site of institutionalization; and how nanoengineering is being consolidated as an entrepreneurial science with social and political consequences.

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40. Ana Viseu, "Caring for Nanotechnology? Being an Integrated Social Scientist," *Social Studies of Science* 45, no. 5 (October 1, 2015): 642-64.

Disciplinary Formation

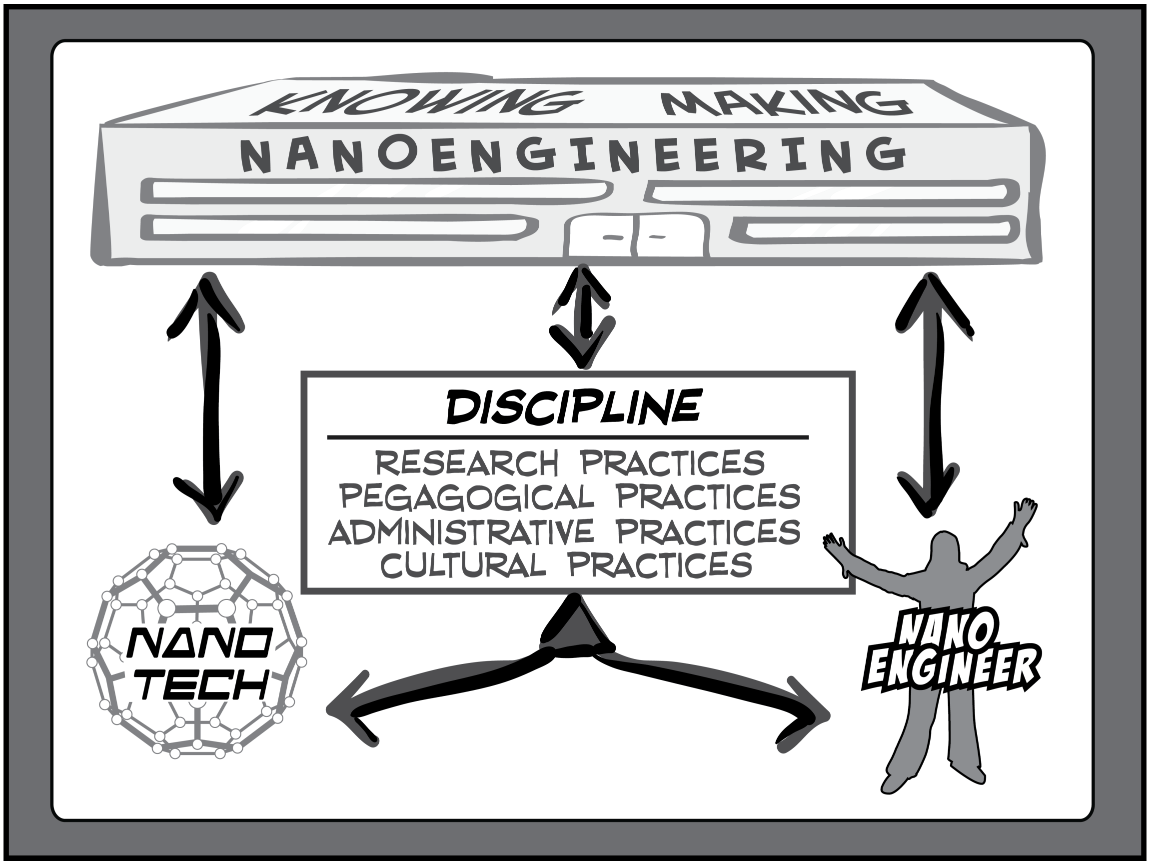

Illustration 21 Disciplinary formation.

Some theorists question the utility of using the concept of discipline as an organizing principle in analyzing scientific practice in what might be a post-disciplinary era or at least an interdisciplinary one.[41] However, insofar as the actors in my field site are actively attempting to construct a discipline, I find this category useful for my analysis, even though I use it provisionally and accept that its character might be unstable (for

41. See Karin Knorr-Cetina, *Epistemic Cultures: How the Sciences Make Knowledge*, Cambridge, Mass.: Harvard University Press, 1999; Timothy Lenoir, *Instituting Science: The Cultural Production of Scientific Disciplines*, Stanford, Calif.: Stanford University Press, 1997; Cyrus Mody, *Instrumental Community*, 2011.

example, in my context nanoengineering is figured as a discipline that is at the same time centrally characterized by its interdisciplinarity). Timothy Lenoir, while avoiding the notion of a discipline as such, argues that a disciplinary program must be understood within its local political economy, as part of a regional knowledge economy.[42] He understands a disciplinary program as a political institution that demarcates areas of academic territory, allocates the privileges and responsibilities of expertise, and structures claims on resources.[43] Such a disciplinary program is embedded in market relationships that regulate the production and consumption of knowledge. As a political institution, it serves as a site for coordinating and embodying skill, and for constructing and sustaining forms of social and cultural identity. He distinguishes between a “discipline” as a universal category and a “disciplinary program” as a local, contingent formation. Following that distinction, when I blur the boundaries between discipline and department, it is because the NanoEngineering Department—my site—is a disciplinary program, a local and contingent formation that is part of a broader push to establish nanoengineering as a distinct disciplinary and professional identity. Each of Lenoir’s characterizations of a disciplinary program is apt for my site. The NanoEngineering Department demarcates academic territory, is embedded in market relationships, embodies skill, and creates identity, among the other attributes Lenoir lists. The name of the department itself is an artifact of the negotiations entailed in demarcating academic territory. Originally conceived as a department of “Nanoscience and Engineering,” the department agreed to change its name to “NanoEngineering” in order to gain the support and endorsement of

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42. Lenoir, *The Cultural Production*, 1997.

43. Ibid, 61.

the physics department, which wanted to maintain the possibility of establishing nanoscience within its purview.[44]

A disciplinary program is also an instrument of disciplinary power, in a Foucauldian sense.[45] But this department does not create identity through panoptic surveillance, though course examinations are mechanisms that make students visible. Nor does it create identity through punishment, though students might fail exams and courses and ultimately leave the major. Rather, by creating the norms of what constitutes a proper nanoengineer, the power of this disciplinary program is a productive one. Students learn to govern themselves to adhere to these norms.

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44. Sadik Esener, Michael Heller, Sungho Jin, Jan Talbot, and Kenneth Vecchio, "Proposal for the Creation of the Department of Nanoengineering (Ne) within the Irwin and Joan Jacobs School of Engineering at the University of California, San Diego." i-175, 2007, 155, 161-2. A letter from the Dean of the Physical Sciences dated January 19, 2007 states that "We are pleased to give our support for the initiative to create a new Department of Nanoengineering in the Jacobs School of Engineering….However, we believe that it is critical that the Division of Physical Sciences and the Jacobs School of Engineering maintain the strength and visibility of their distinct *nano* research profiles and we welcome your agreement on this issue." Two following letters from the Dean of the Jacobs School and from one of the founding faculty dated January 29 have the subject line "Request for Name Change for the proposed Nanoscience and Engineering Department." The latter states: "The Dean and Department Chairs of Physical Sciences brought to our attention their interest in preserving the term 'Nanoscience' for their use in future programs within their division. Since it was not, and is not, our intent to limit the ability to grow in this area, and in fact, are encouraged by their future planning in Nanoscience, we have agreed to rename the proposed department in the Jacobs School, 'NanoEngineering.'"

45. Michel Foucault, *Discipline and Punish : The Birth of the Prison*. 2nd Vintage ed, New York: Vintage Books, 1995. Foucault writes: "'Discipline' may be identified neither with an institution nor with an apparatus; it is a type of power, a modality for its existence, comprising a whole set of instruments, techniques, procedures, levels of application, targets; it is a 'physics' or an 'anatomy' of power, a technology" (215).

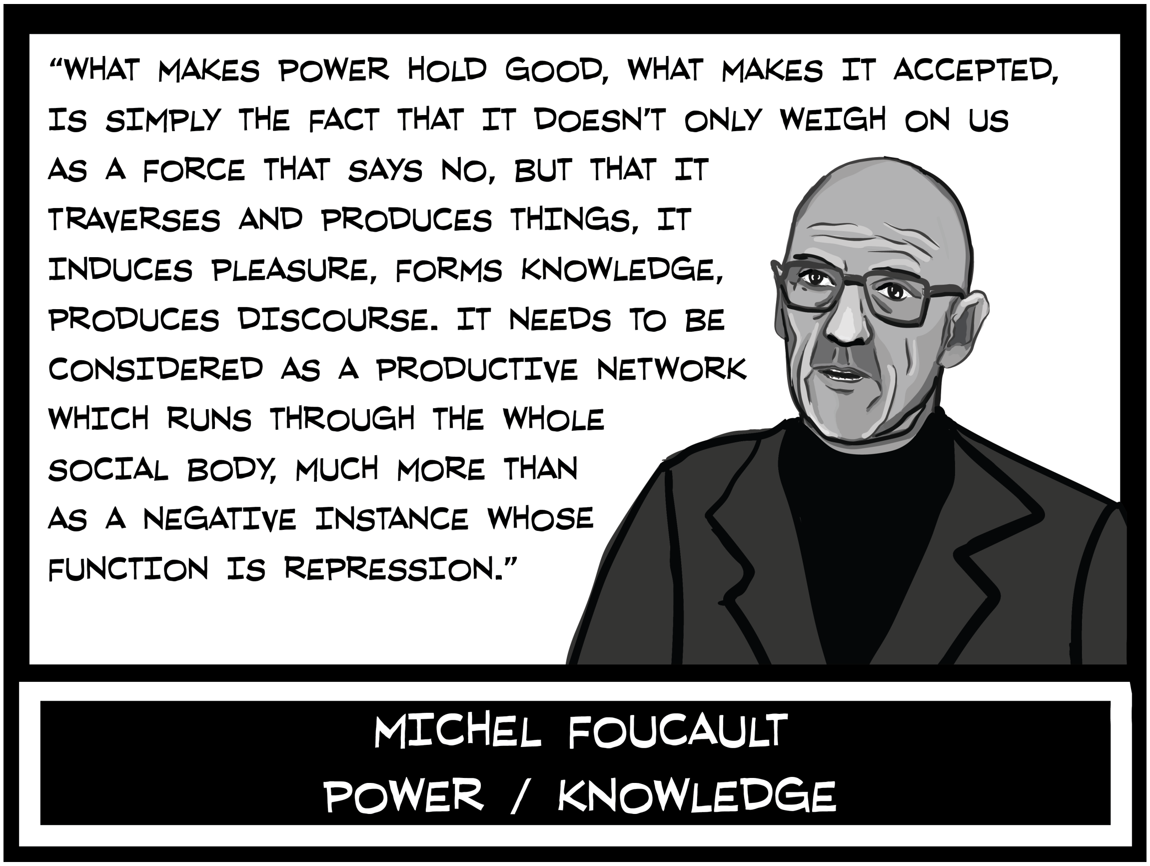

Illustration 22 Foucault on the productive nature of power. "What makes power hold good, what makes it accepted, is simply the fact that it doesn't only weigh on us as a force that says no, but that it traverses and produces things, it induces pleasure, forms knowledge, produces discourse. It needs to be considered as a productive network which runs through the whole social body, much more than as a negative instance whose function is repression."[46]

Following Donna Haraway—particularly through her work in *Primate Visions* (1989)—I examine disciplinary formation through storytelling and origin stories. And, following Sharon Traweek, I focus particularly on what is uncontested in the common sense view of the world that is being produced in this site.[47] Haraway shows that scientific practice is itself a kind of story-telling practice,

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46. Michel Foucault and Colin Gordon, *Power/Knowledge : Selected Interviews and Other Writings, 1972-1977*, New York, N.Y.: Pantheon Books, 1980, 119.

47. Traweek, *Beamtimes and Lifetimes*, 1988.

> A rule-governed, constrained, historically changing craft of narrating the history of nature. Scientific practice and scientific theories produce and are embedded in particular kinds of stories. Any scientific statement about the world depends intimately upon language, upon metaphor. The metaphors may be mathematical or they may be culinary; in any case, they structure scientific vision. Scientific practice is above all a story-telling practice in the sense of historically specific practices of interpretation and testimony.[48]

To say that scientific practices and theories "produce and are embedded" in stories and that they structure scientific vision is to point out that facts do not precede language, that it is not Nature that is being narrated but the *history* of nature, and that fact and fiction are kin. It also highlights the historically situated, contingent character of scientific practice—the kinds of stories a particular community tells, the methods and styles of interpretation and testimony that are sanctioned and valued, and the rules that govern material-discursive practices, are culturally and historically specific.[49] Such stories and narratives are not merely linguistic mediations between the natural world and scientific vision, but are part of the material-discursive apparatuses that produce both the natural world and scientific vision as such. I show how nanoengineering's stories are stories of nano worlds, precision medicine, controlling and manipulating matter, self-assembly of

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48. Haraway, *Primate Visions*, 1989, 4.

49. To say that knowledge production is "culturally specific" does not indicate what level of granularity is implied: there are characteristics of western modes of knowledge production that are shared, but even western scientific practice is not monolithic. There may be national and disciplinary differences that can be understood as cultural differences. For example, as Sharon Traweek shows in her analysis, disciplinary practice can have national characteristics (thus, high-energy particle physics in Japan differs from that in the United States along some nationally-inflected lines) (Traweek, *Beamtimes and Lifetimes,* 1988); as Karen Knorr-Cetina demonstrates in her work, different disciplines (such as biology and high-energy particle physics) have very different ways of knowing (Knorr-Cetina, *Epistemic Cultures*, 1999); and as Timothy Lenoir suggests, scientific institutions and labs are always specific sites of cultural production and embedded in specific political economies (Lenoir, *The Cultural Production*, 1997).

nanoscale materials into larger structures, and technological progress, often situated within what Colin Milburn refers to as the “small worlds, endless frontiers” of nanodiscourse.[50]

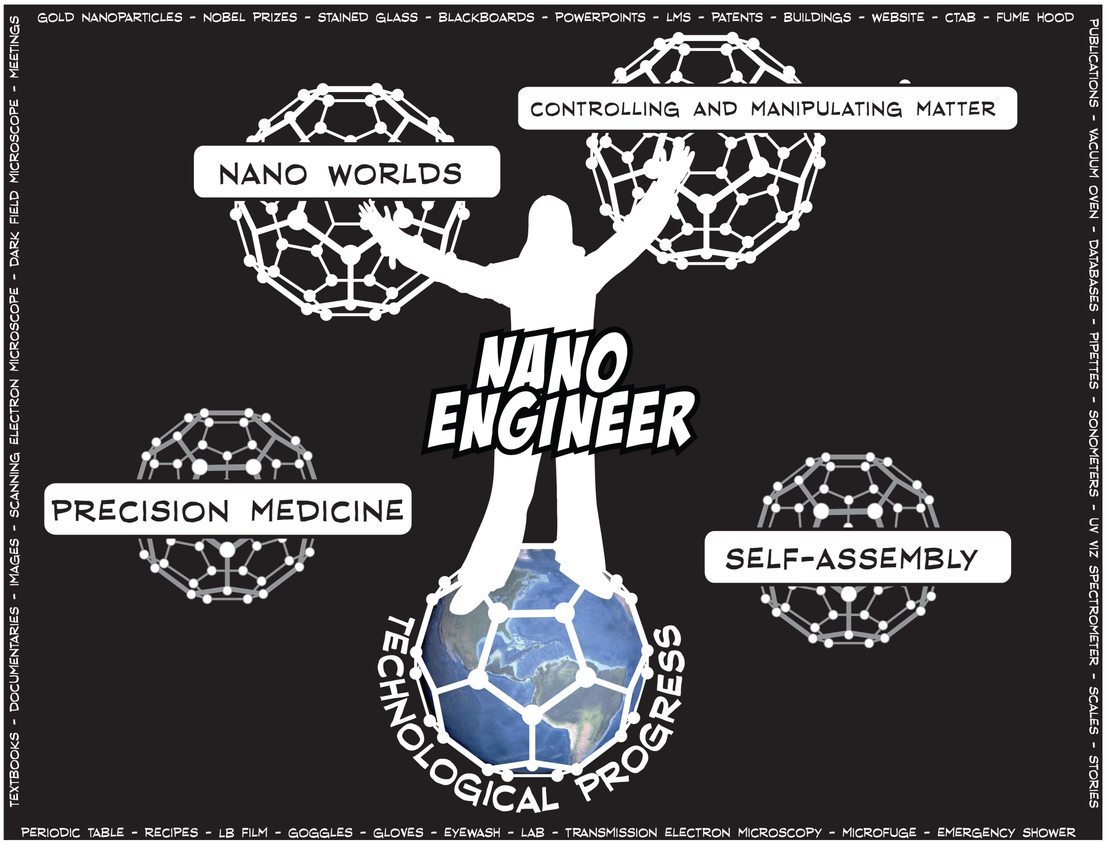

Illustration 23 Nanoengineering stories. Globe image courtesy of NASA.

Haraway also reminds us that the authority of an origin story lies in part on its intertextuality, the way origin stories presume other origin stories. I will show how the above stories are related, how they form through popular culture, imagined futures and imagined histories, and how they are particularly intertwined with stories of innovation

50. Milburn, *Nanovision*, 2008, 78.

economics and technological capitalism.[51] These stories form the common sense of nanoengineering, and I will highlight what is uncontested and what is left out of these stories.

In order to understand the Department of NanoEngineering as an institutionalization of a disciplinary program, I engage in the following lines of inquiry: By what means does the department establish a disciplinary and professional identity? How is this disciplinary program embedded in market relationships and in what sense is it cast as an "innovation ecosystem" in the words of the chair of the department? How do these market relationships inflect practices of both knowledge production and identity production within the department? Who are the key players in establishing this department, what visions and values have been and are being harnessed to the bureaucratic authority of the university to create and sustain it, and what social strategies are at work in affirming and claiming power within and through it? What are nanoengineering's stories, how are they related, and how do they produce the common sense of nano's imaginaries? While some of these lines of inquiry are more prominent in some chapters rather than others, I intentionally avoided attempting to consolidate disciplinary formation into one chapter. If disciplinary formation is intimately tied to what nanoengineering is—its histories and futures, its values and goals, its practices and pedagogies—it must be a part of each of these chapters.

51. Luis Suarez-Villa, *Technocapitalism: A Critical Perspective on Technological Innovation and Corporatism*, Philadelphia: Temple University Press, 2009. Suarez-Villa defines technocapitalism as "a new form of capitalism that is heavily grounded on corporate power and its exploitation of technological creativity" (4). I do not use the term "technocapitalism" because I do not want to make the argument that this is a new form of capitalism, but I do want to pick up on Suarez-Villa's argument that corporate power and the exploitation of technological creativity are central to contemporary modes of innovation in the United States, and to the research regimes within which this nanoengineering department has formed.

A Brief Introduction to My Site

A key thread of this dissertation concerns how nanoengineering comes to be understood as innovation for the benefit of society. What is meant by the terms "innovation," "benefit," and "society," and how, taken together, do they constitute a commitment to progress that serves as the justification and ethical imperative of a new field, discipline, and educational program? What is the role of the market in facilitating this mission, and how does this relationship to the market help constitute nanoengineering as an entrepreneurial technoscientific practice? Central to the constellation of these terms is the idea of translation, connoting the transmutation of research into assemblages of meaning and matter and thence into social and economic benefits.

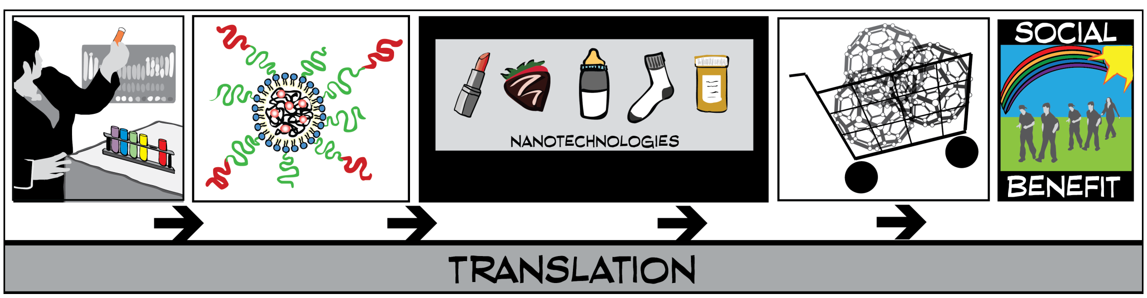

Illustration 24 Translation.

Two statements from the first department chair serve as useful starting points. First, he calls this nanoengineering department an "innovation ecosystem."[52] As a metaphor, this phrase works to naturalize and harmonize the elements of the nanoengineering department in a public university with the broader environment—

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52. Interview with Chair, January 25, 2012.

including its state and industry partners—within which it operates, with innovation as the purpose and product of its labor. Second, the chair maintains that bachelors degrees are necessary in order to establish a nanotechnology industry.[53] As an imperative, the mission to produce the requisite labor for a nascent industry broadens the scope of innovation. What is being innovated and produced exceeds the particular nanotechnologies that may be crafted in this site to include also affordable labor power—in the form of "bachelors degrees"—that is intimately connected with establishing a new industry. Though my language for describing this in terms of multi-scale worlding and coproduction is not identical to what nanoengineers in my site would use, it is compatible with the ways that they see themselves as in fact innovating across these scales.

This department understands itself as innovating institutionally and educationally through the formation of the world's first nanoengineering department and one of the first undergraduate majors. The undergraduate program is central to the department not only because such skilled labor is necessary for an industry, but also because it serves as the anchoring and defining commonality that secures nanoengineering as a field and disciplinary and professional identity. In a very real sense, the nanoengineering undergraduate program perhaps even more than nano as such serves as that which the faculty and other members of the department have in common, orienting and redefining their varied disciplinary origins, training, and current research projects toward nanoengineering. According to the department's proposal: "Our proposed NanoEngineering degree program is the very heart and soul of our department. We could

53. Introductory NanoEngineering lecture and in informal comments to me, 2011. This sentiment is also stated explicitly in the department proposal.

not place any higher value on it, as the NanoEngineering degree is essential to our namesake and existence."[54] I suggest that these words should not be taken as hyberbole. While it may be true that establishing an undergraduate major is critical to any efforts within a public university to establish a new department, I suggest that particularly in the context of a field that is not itself established, the undergraduate major is important for establishing an identity. It is through the production of a new generation of nanoengineers that something comes to be consolidated as nanoengineering.

This department is located in a public university with a strong and reputable engineering school that has a history of leading the "biotechnology revolution" and establishing a close relationship between the university and industry in the 1980s.[55] The establishment of this department in this locale builds on local and regional development of high-tech innovation regimes that privilege the figure of the scientist-engineer-entrepreneur. Through this site, and particularly through an undergraduate program, the department can structure and mobilize resources and expertise and play a leading role in establishing a disciplinary and professional identity for nanoengineering. This identity is one that is centrally concerned with innovation as an interdisciplinary and entrepreneurial mode of world-making.

The first chair of the department cited as the originary moment of this department a lunchtime conversation with colleagues about their shared desire to realize the vision of

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54. Proposed Undergraduate Program Leading to Bachelor of Science in NanoEngineering, Jacobs School of Engineering, 2009, 5.

55. The San Diego Technology Archive at UC San Diego's library contains archives of this history, including oral histories: http://libraries.ucsd.edu/sdta/sectors/life-sciences/index.html, accessed March 11, 2016. I briefly worked as an intern for the San Diego Technology Archive in 2011-12.

the 1966 science fiction film *Fantastic Voyage*. It turned out that each of the three having lunch that day had been inspired by the film as young people.

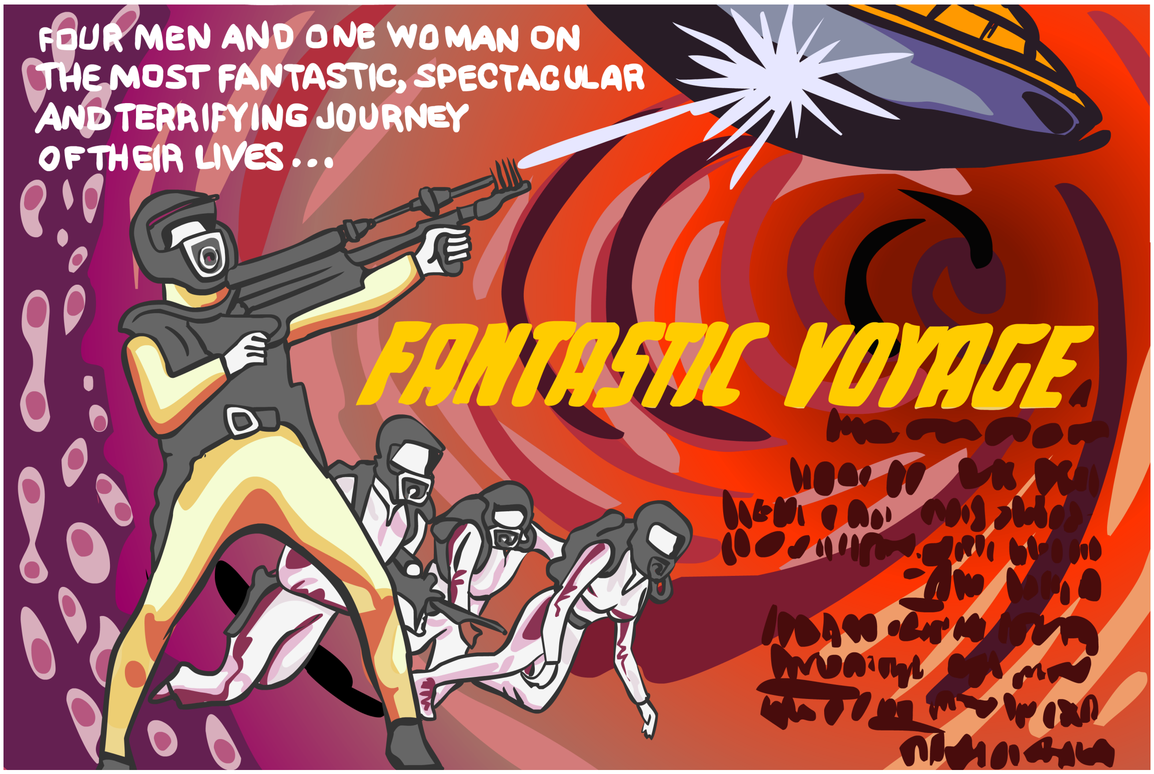

Illustration 25 *Fantastic Voyage* poster.

In this conversation, they decided that it would be impossible to do the kind of multidisciplinary research necessary to realize this vision—which they understand as a vision of nanomedicine and targeted drug delivery—and they decided they needed to start a new department.[56] Establishing a new department would allow them to build something from the bottom up, a recurring theme in nanoengineering imaginaries. Specifically, rather than piecing a department and curriculum together by cross-listing current faculty from other departments—which, they feared, would be difficult bureaucratically and

56. Informal discussion with Chair over lunch, October 11, 2012.

would not enable truly innovative research—they wanted to hire new faculty. The undergraduate program proposal states:

> In addition, given the inherently multi-disciplinary nature of the field, involving physics, chemistry, biology, electrical engineering, mechanical engineering, and materials science, among others, it would be very rare to find any existing academic department with a faculty that can cover this broad spectrum with in-depth courses in nanoscale science and engineering. However, the NanoEngineering Department's faculty has been specifically assembled to meet this challenge.[57]

The "multi-disciplinary nature of the field" is seen here as a primary justification for establishing a new department. Having established the first such department in the United States, the founding members of the department highlight that it has achieved the multidisciplinarity it aspired to. The proposal continues:

> At the Jacobs School of Engineering, it was recognized a few years ago that the time was ripe to take nanotechnology education to the next higher level and founded in July, 2007 the Department of NanoEngineering—the very first academic department in nanotechnology in the United States. Since then, the department has grown to have 16 faculty members whose expertise covers the whole spectrum of physics, chemistry, biology, bioengineering, chemical engineering, electrical engineering, materials science, and mechanical engineering.[58]

What is different between cross-listing existing faculty from these different disciplines and bringing them together into a new department in terms of innovation? While there were pragmatic considerations including obtaining money to support new hires, establishing a new department also made it possible to form a disciplinary and

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57. Proposed Undergraduate Program Leading to Bachelor of Science in NanoEngineering, Jacobs School of Engineering, 2009, 4.

58. Ibid., 2.

professional identity for nanoengineering by bringing in new faculty not just to teach courses in nanoengineering but to become nanoengineers.

Additionally, these faculty were not just picked to assemble a multi-disciplinary team and curriculum, but also for their interest in being part of an entrepreneurial environment. Specifically, they would be "risk takers" by definition if they were willing to move to this brand new department in the not-quite-legitimated field of nanoengineering.[59] This kind of risk-taker is what they wanted in order to fulfill the mission of enacting an "innovation ecosystem." (This is particularly important for understanding why, perhaps, I did not encounter more friction or disagreement among the faculty regarding the entrepreneurialism or other aspects of the department's research and pedagogical practices). Yet establishing a new department in a university is not easy, and in their proposal for a new department the founding members (who authored the department proposal) included endorsements from the chairs of other science and engineering departments as well as from industry leaders who confirmed they would strongly support the establishment of such a department. An engineering school press release published when the department was established in 2007 describes it as "supported by faculty in the five other departments at the [Jacobs School of Engineering]."[60] It further outlines a "leadership team" representing these five departments as the "driving force for creating the new department." This statement speaks to the need to show—even after the department was established—that its existence was widely supported internally

59. Interview with Chair, January 25, 2012.

60. UC San Diego Jacobs School of Engineering Press Release: http://www.jacobsschool.ucsd.edu/news/news_releases/release.sfe?id=675, accessed 06/29/2015.

as well as externally. Moreover, establishing the rhetoric of entrepreneurialism that is prominent in the department, the news release goes on to indicate that:

> In the past five years alone, the five members of the leadership team filed 51 patent applications and licensed 6 inventions to private companies. Those professors and their fellow faculty members will continue to work closely with the …Center for Entrepreneurism and Technology Advancement and [the] …Technology Transfer and Intellectual Property Service office to accelerate the commercialization of discoveries and prepare engineering students to contribute to the local, national, and global entrepreneurial workplace.[61]

This is a press release with multiple audiences and purposes. Speaking to the broader public as well as to other members of the university, it articulates its justifications for the new department. But it can also be read as signaling its concerns. By "concern," I mean to suggest both what may worry the department and school and what these entities are interested and engaged in.[62] First, as a newly established entity that has won the approval of the university's academic senate, the department is still concerned to communicate that it has wide support internally and externally, that it is uncontroversial and unblemished by internal naysayers or doubters. This lends credibility to its justification for existence in that it signals that nanoengineering is a matter of concern between existing members of the engineering school and department and between the university and industry. Second, the press release communicates nanoengineering's entrepreneurial focus that entails innovating in partnership with industry and creating an entrepreneurial labor force prepared to enter industry. The latter concern regarding labor led to the establishment of

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61. The same press release is also here: http://www.calit2.net/newsroom/release.php?id=1123.

62. Bruno Latour, "Why Has Critique Run out of Steam? From Matters of Fact to Matters of Concern," *Critical Inquiry* 30 (2004): 225-48. Latour distinguishes between "matters of fact" and "matters of concern."

the Ph.D. and M.S. degree programs in 2009, and the undergraduate degree program in 2010.

The undergraduate degree program in particular is deemed essential to establishing a nanotechnology industry. The first chair of the department in an interview with me and then in the following words in a lecture to incoming undergraduate nanoengineering majors, articulates a key relationship between the undergraduate degree program and a new industry:

> It became obvious that there was enough new engineering principles and science underlying this field that we needed to create a curriculum to start teaching you all about it so that we could move the field further. It has been my strong belief that every engineering field that has been a major industry around the world has succeeded not because of a bunch of PhD's doing stuff, but because [..] of the education of bachelors level engineers who go and work in those industries. And you can look at that in terms of the nuclear power industry, the aircraft industry, the semiconductor industry, the computer industry, civil engineering, every field that has had very significant growth as an industry has succeeded in that growth because of the ability to produce engineers with bachelor level degrees. They are the workforce of those industries. So we believe that for this industry really to grow, we need to have a workforce of largely bachelor level engineers.[63]

Here, the chair closely ties the production of "bachelors level engineers" to the production of a major industry, comparing an emerging nanotechnology industry to more established industries in other engineering fields. In my discussion with him, and here more implicitly, this is linked to the cost of labor—bachelors level engineers have the skillset to become the "workforce" without the pricetag of Ph.D.s, although certainly there must also be a question of numbers since fewer students are able to complete Ph.D.

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63. Introductory NanoEngineering Course Lecture, January 5, 2011. There is also similar language in the department proposal.

programs. In establishing this curriculum there is an explicit attention then to the production of (skilled) labor power as a requisite element of an industry. In this way, the nanoengineering department links itself to the production of a nanotechnology industry, connecting the university to industry not just through collaborative work or licensing relationships but through the production of a skilled workforce. Additionally, the chair's claim that the educational program is required in order to "move the field further" implicitly distinguishes between a field and an industry in that he highlights fields that have had "significant growth" *as* industries. Through this distinction, then, he also links the production of labor power to the consolidation and development of the field of nanoengineering.

The implicit temporal linearity between these forms of production from the chair's perspective do not at first glance fit within the analytic of coproduction. He describes the new principles that underlie the field as justifying the creation of the undergraduate educational program, which in turn will produce bachelors level engineers, which in aggregate are necessary for the establishment of an industry. Yet, as I will show, these forms of production do not occur in a sequential or itemized way. Moreover, the chair's statement that producing these engineers is essential to producing an industry and to developing the field is an important part of the story, but not the whole of it. As quoted previously, the department's formal proposal for the undergraduate program states in clear terms the import of this undergraduate major to the very "namesake and existence" of the department. I would propose to take this literally. Each of the faculty is the PI of her own laboratory, which functions somewhat analogously to a start-up in an incubator in that the PI must procure funds, select research projects, and assemble a team to conduct the labor of these projects, with the aim of innovation. Each PI comes from a disciplinary background that precedes nanoengineering—representing chemical engineering, physics and computational engineering, electrical and mechanical engineering, bioengineering, and materials science. Prior to joining this department and becoming a professor of nanoengineering, none of these faculty would have introduced themselves as nanoengineers, even if their research engaged the nanoscale. Indeed, even now according to my interviews, there is some variation in how they would identify privately or publicly, some more comfortable with the title "nanoengineer," others indicating that the label is unimportant, and/or that the way they introduce themselves depends on the audience.[64] Without an undergraduate nanoengineering program consolidating a nanoengineering curriculum for which these faculty are professors of nanoengineering it is not clear that there would be enough glue to make it all stick together much less to produce nanoengineers.

64. Interviews with NanoEngineering faculty, 2012-13.

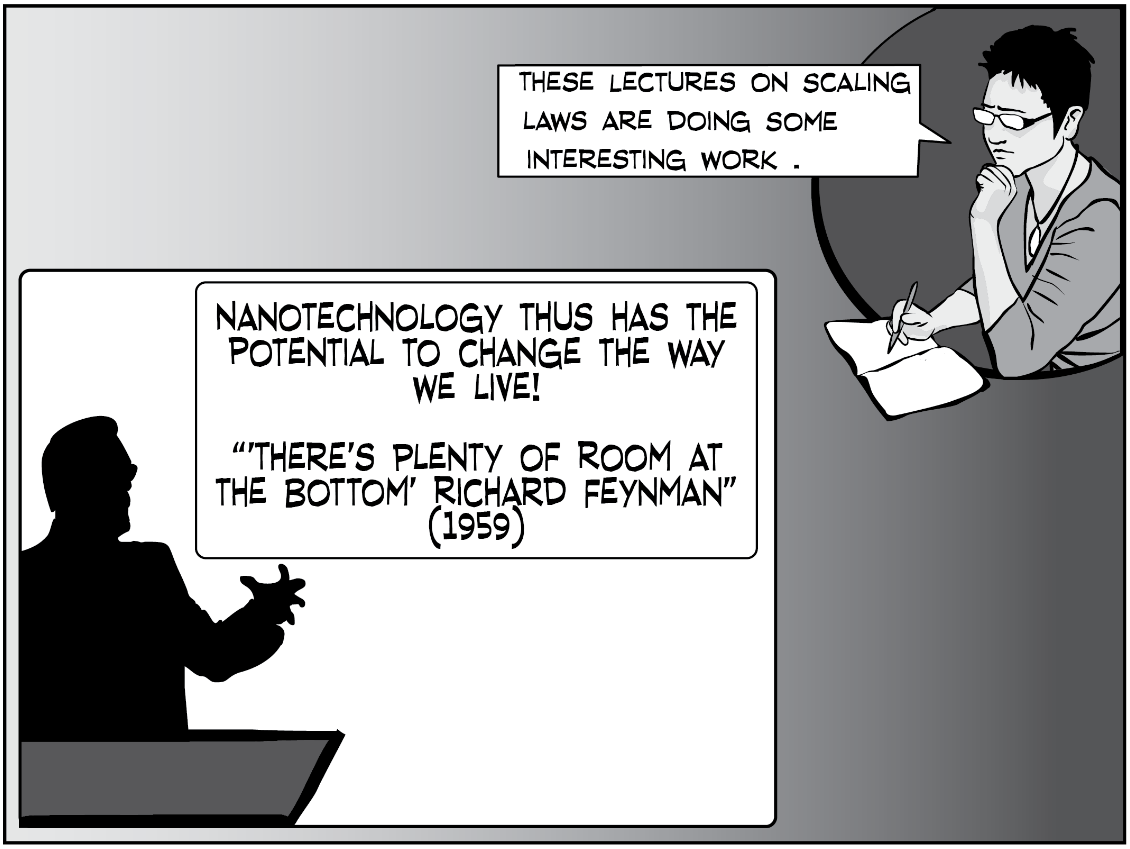

Illustration 26 The professor becomes a nanoengineer in the classroom as much as in the laboratory.

It is in the undergraduate program where incoming students are expected to become nanoengineers that the faculty have to do the work of establishing the disciplinary and professional identity of the nanoengineer that is an essential product of a nanoengineering department. This production is not just that of the student into a nanoengineer, but that of the professor who performatively and iteratively becomes a nanoengineer in the process as well. It is the *doing*—including teaching and learning—of nanoengineering that constitutes the nanoengineer, and this doing is made possible in part through institutionalization, where nanoengineering is constituted as a set of technocultural practices. The nanoengineering undergraduate program, the nanoengineering department, and the nanoengineer (both professor and student) emerge through such institutionalized practices.

Central to the claims of innovation at this site is that nanoengineering is innovation for the benefit of society. Innovation and entrepreneurialism are mutually articulated to construct nanoengineering as an entrepreneurial endeavor, and this entrepreneurialism is validated as necessary for effectively translating research to society to be used. Benefit is one of the key elements of the common sense worldview of nanoengineering. It is the key uncontested element in the stories of what nanoengineering is and what it will do. While nanoengineers can and do acknowledge that there are risks—understood as always and inevitably present in all innovation—they overwhelmingly see nanotechnologies as producing enormous societal benefits, particularly in energy, medicine, and materials. Whether applying for funding from the NSF or spinning off a company, nanoengineers must develop a professional vision that sees benefit resulting from their research. In this context, benefit is usually articulated in universal terms.

Chapter Overview

In Chapter 2, "*Fantastic Voyage* and the Consolidation of a Discipline," I consider the role of popular culture within scientific communities, and the ways in which framing cultural objects entails exclusions that matter in constructing an identity.

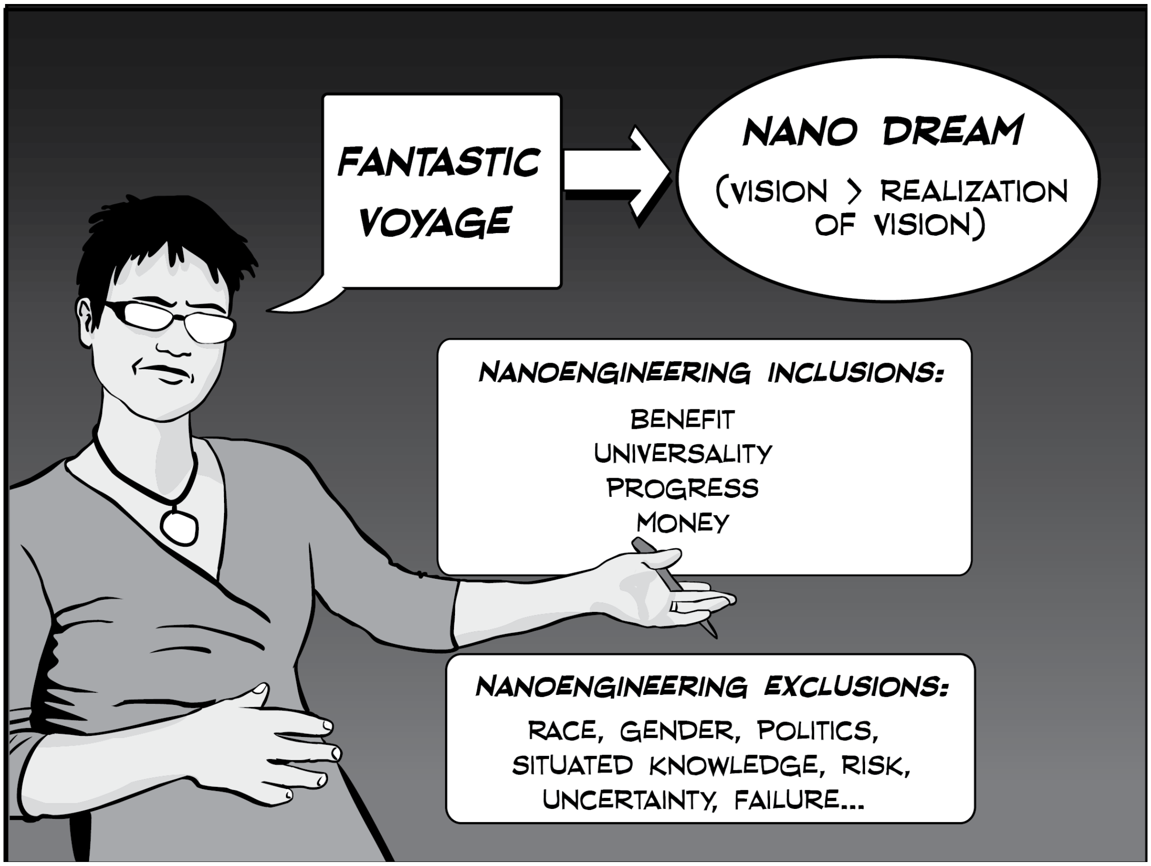

Illustration 27 In the framing of the film in the undergraduate classroom, some things are included, and other things are excluded. I argue that both inclusions and exclusions are important in the construction of a nanoengineering identity.

Fantastic Voyage, a 1966 Hollywood science fiction film, is used by this department to craft a narrative about what nanoengineering is, what it promises to be, and how nanoengineering students should orient their careers around a "nano dream" of a future nanotechnology that will benefit society. Bringing together ethnography, film studies, and feminist science studies, I juxtapose my analysis of how the film is used in the department with a close reading of the film itself to examine how the department's framing of it—such as the inclusion of the film's medical aspects and exclusion of its Cold War military context—contributes to the production of a nanoengineering identity. I argue that *Fantastic Voyage* and the nano dream become boundary-drawing practices through which the nanoengineer is imagined as an intrinsically ethical identity. This chapter contributes an empirical analysis of how popular culture gets enrolled in the production and consolidation of a scientific disciplinary program.

Next, I examine the ways in which moral values and worldviews get embedded in what nanoengineers would understand as technical education. In chapter 3, “Smaller is Better? Learning an Ethos and Worldview in Technical Education,” I examine the curriculum in an introductory nanoengineering course that teaches students about scale. Building on feminist science studies and communication theory, I argue that this curriculum implicitly teaches students an abstract and universal notion that smaller is better. I suggest that rather than smaller *is* better, a perspective that embraces context and specificity as illustrated, for example, by the question “when, how, and for whom is smaller better?”—would ground nanoengineering in a more reflexive, pluralistic and democratically-oriented mode of world-building. This chapter contributes an analysis that highlights the import of the higher-ed classroom as a site of knowledge production, showing how values and knowledge are intimately connected in science pedagogy, and demonstrating the value of communication theory to STS analyses.

In chapter 4, “Self-Assembly and the Invisible Hand: Producing the Autonomous Individuals of a Discipline,” I examine the nanofabrication process of self-assembly—central to many of the promises of nanoengineering—to consider how ideologically laden metaphors materially drive knowledge production and world-building. Self-assembly refers to a range of practices that employ “bottom-up” methods of fabricating nano structures. Rather than individually placing each element into a structure, bottom-up techniques create conditions in which the elements predictably assemble themselves into a desired structure.

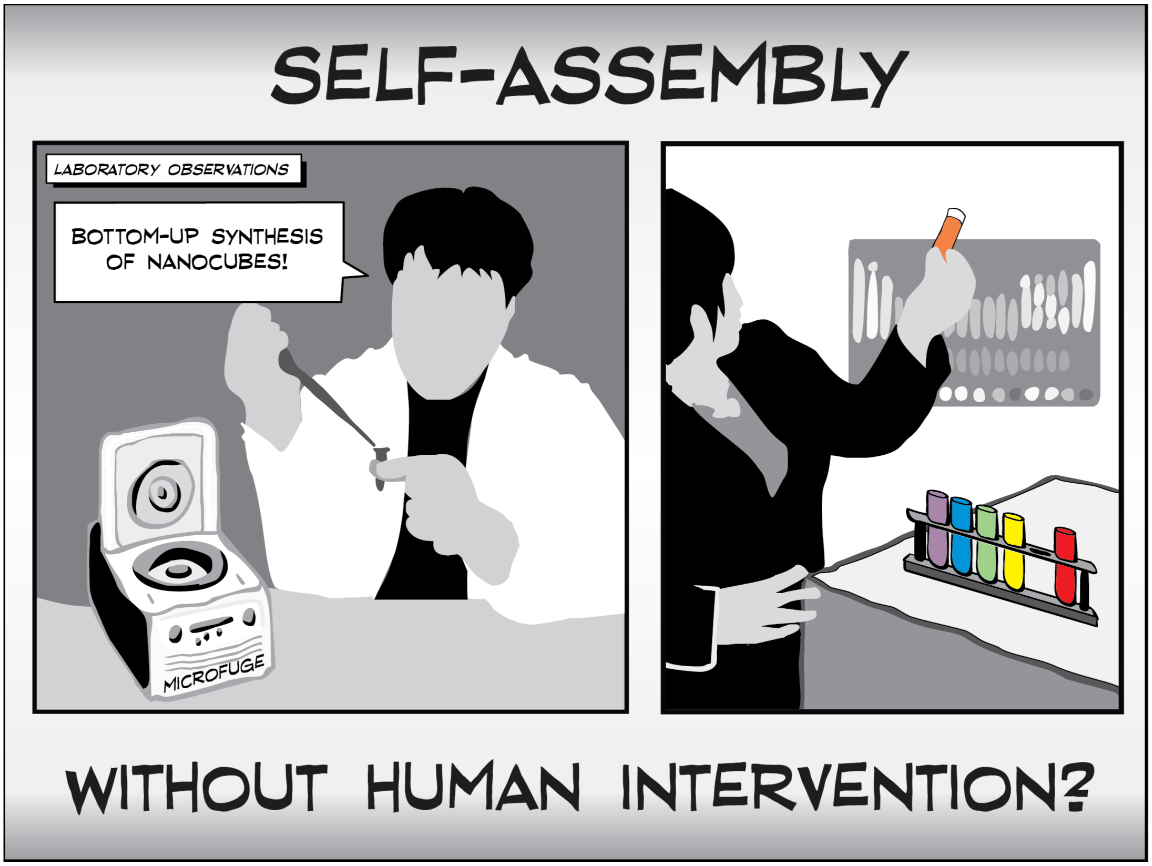

Illustration 28 Self-assembly without intervention.

Self-assembly is often described by nanoengineers as occurring without human intervention, or without a human hand. I draw on laboratory observations and historical and contemporary texts in and outside my site to show how self-assembly comes to embody assumptions about a naturalized, rational individualism and freedom. I theorize the dynamics of autonomy and discipline in the practices of assembling selves across scale, and in so doing, I highlight the parallels between nanocubes, nanoengineers, and this nanoengineering department. That is, I suggest that nanoengineers too are figured as self-assembling individuals, autonomous in their pursuit of nano dreams, even as they simultaneously must become nanoengineers within a particular set of conditions that enable one particular mode—an entrepreneurial mode—of doing nanoengineering. They must understand themselves as entrepreneurs even as they are constituted as labor within the broader apparatuses of innovation. This chapter highlights the laboratory as an important site of pedagogy and disciplinary production as much as it is a site of knowledge production. It further builds on STS strengths in attending to language and metaphor by showing how the trope of self-assembly articulates knowledges and practices of nanofabrication in terms that are steeped in liberal and neoliberal logics.

In Chapter 5, "Producing Human Capital For a New Industry," I examine how the institutional imperative to produce human capital materializes in the undergraduate curriculum. I argue that it manifests primarily in the entrepreneurial attitude that students are supposed to attain through their experiences as nanoengineering students, and that human capital theory threads the needs between two imperatives important in the undergraduate curriculum that are in tension with each other. The first, that of the nano dream, figures the nanoengineer as an entrepreneur, pursuing her own dreams of nanotechnological progress that will benefit society. The second, that she is the workforce for a new industry, figures the nanoengineer as the technical labor on an industrial team. I examine how these bachelors degrees might comprise a "standing reserve" of high-tech vocational labor who are required to see themselves as self-investing entrepreneurs.[65] Cautioned that they should prioritize their major classes and fit their GE's around these demands, even if it means they should finish their GE's over the summer, students compete for the grades, internships, and laboratory research positions that will enable them to be successful in their career trajectories. Yet only a small portion will have the opportunity to get the lab positions and internships that will enable them to pursue a graduate degree and a leadership position. The individuating production of little capitals in the pursuit of nano dreams elides the class differences that advantage students who do not need paid jobs to make their way through college, and perpetuates the myth that each nanoengineer will be able to pursue her own nano dream if she works hard enough. Bringing political theory and critical university studies to STS, I show how the production of engineers as human capital is intimately tied to the mode of knowledge production engaged by the university and its role in the knowledge industry.

In Chapter 6, "Translational Research In An Innovation Ecosystem," I consider how the institutional imperative to produce intellectual capital materializes in the department. Considering this imperative alongside three claims the department makes—that it does translational research, that it is an innovation ecosystem, and that it is

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65. Chandra Mukerji, *A Fragile Power : Scientists and the State*. Princeton, N.J.: Princeton University Press, 1989; Wendy Brown, *Undoing the Demos : Neoliberalism's Stealth Revolution*, First Edition, New York, Cambridge, Massachusetts: Zone Books, MIT Press, 2015.

In Mukerji's account of soft-money scientists, she argues that scientists are being funded by the state not so much for the information they provide to the state but for their availability to the state when the state requires them. In this analysis, she shows that this 'standing reserve' of labor is more akin to a military reserve than laborers on welfare, though these scientists too are dependent on the state. Yet with nanoengineers, the parallel can be drawn more strongly to laborers who go on and off welfare as the economy fluctuates. Though ostensibly they receive a liberal arts education, they are primarily receiving vocational training to be high-tech laborers in industrial labs whose vulnerability to market fluctuations may be the same as other laborers. The reference to 'little capitals' is an invocation of Wendy Brown's analysis of neoliberal rationality, in which she argues that citizens as *homo politicus* are being refigured as little capitals or firms that are not only entrepreneurial but who have to perpetually attract investors and who are vulnerable to redundancy.

innovating for the benefit of society—I argue that the paradigm of translational research is taken up as the right tool for the job of consolidating nanoengineering as a disciplinary program within this institutional imperative of producing intellectual capital. The framework of translational research unites the utopian horizon of nanoengineering with the utilitarian means of achieving efficient, rational, progressive innovation, from lab to society; it articulates nanoengineering's benefits in terms of universal inclusion even as it requires commercialization through the marketplace, where value is predicated on exclusion; it enacts a mode of governance for innovation; and it figures the nanoengineer as a translational figure which, I argue, fits the bill for how the nanoengineer understands herself, particularly in relation to her ability to communicate across scale, discipline, and institutional boundaries. Figuring all research as economic conduct, it also grants the nanoengineer some agency in how she articulates herself and her research toward the market, so long as she does so. This chapter contributes a theoretical understanding of nanoengineering and its constitution as an entrepreneurial science that is centrally predicated on market logics, as well as how institutional dynamics inform the disciplinary formation of a field.

In my conclusion, "A Future History of Nanoengineering," I consider potential future histories of nanoengineering with particular attention to the question of how we choose to educate scientists and engineers. I opened this introduction with a quote from Hannah Arendt, in which she proposes that we must "think what we are doing." Yet my study of this nanoengineering department and undergraduate major suggests that nanoengineering students are not learning to think what they are doing. While they may be exposed to critical thinking in their general education classes or elsewhere, the nanoengineering curriculum does not train students to reflexively engage the complex social, political, and ethical dimensions of nanoengineering. I argue that such training constitutes a critical skillset for conducting nanoengineering responsibly and successfully. This does not mean that students will be incapable of demonstrating such reflexivity in their work after they graduate, and it also does not mean that such reflexivity will necessarily avert or even mitigate any particular failure or downside. This is not a story about utopian or dystopian futures, or a proposal for a program or strategy that will ensure a universal, beneficial outcome. But with power and capital invested in structures of high-tech innovation that have weak regulation or oversight, what consequences might we face as a society if those at the forefront of such innovation, with the technical know-how to remake the world according to their dreams, do not know how to think what they are doing?

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Chapter 2 *Fantastic Voyage* and the Consolidation of a Discipline

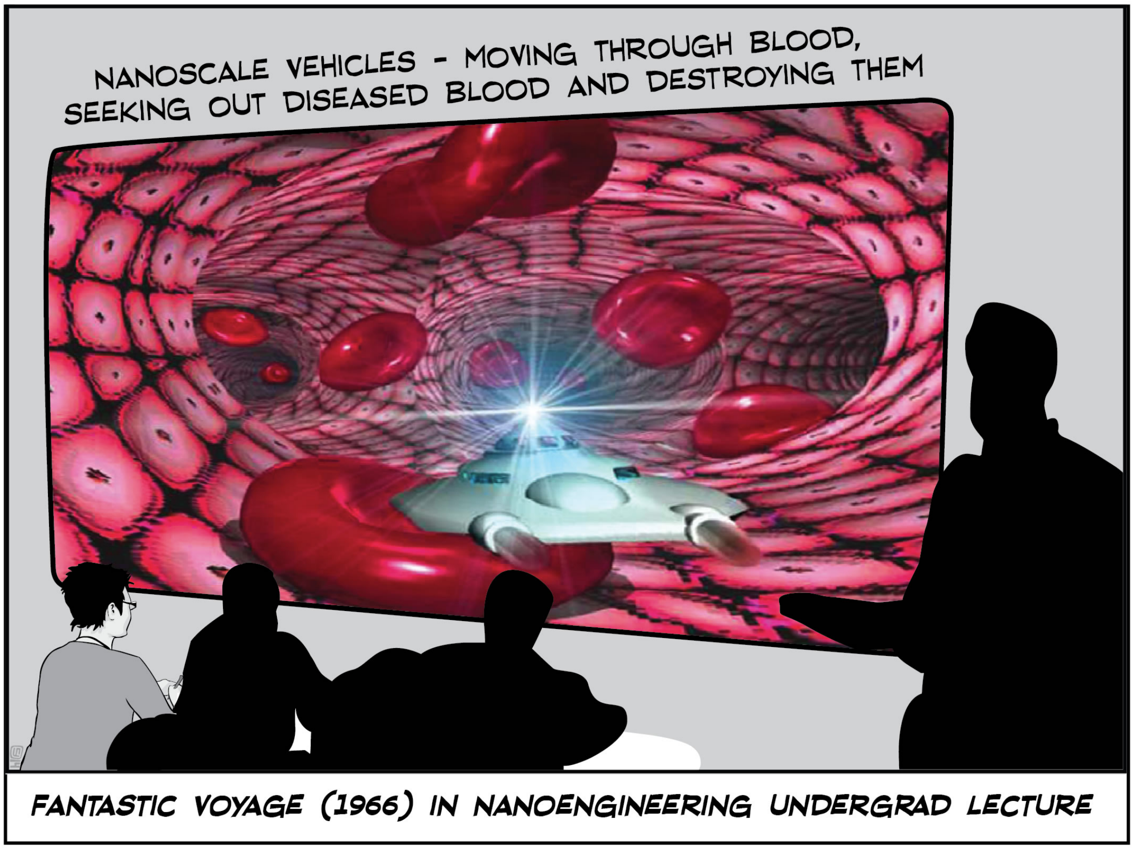

Illustration 29 *Fantastic Voyage* in an introductory nanoengineering course. Author invokes fair use of original film image.

Introduction

Fantastic Voyage, a 1966 Hollywood science fiction film written by Harry Kleiner[1] and starring Stephen Boyd and Raquel Welch, is often associated with contemporary nanotechnology imaginings.[2] While the depicted voyage is one into the

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1. The screenplay was written by Harry Kleiner adapted from a short story by Otto Klement and Jerome Bixby. The novel by Isaac Asimov was produced after the film version and based on the film.

2. For example, see Michael Berger, "Another Nanotechnology Step Towards 'Fantastic Voyage'," http://www.nanowerk.com/spotlight/spotid=19378.php, 2010; Robert A. Freitas, Jr., "Nanomedicine Art

microscalar confines of the human body, the fantastic voyage often promised by nano enthusiasts is one that traverses both space and time: into the "nano world" (1-100 nanometers); into the macroworlds of medicine, energy, information technologies, environmental cleanup, and war; and into the deep past and distant future. But this film is not only invoked in popular communications about nano. It is also invoked within scientific communities. In this chapter, I will show how the film is used in the NanoEngineering Department to establish a distinct disciplinary history and professional identity for nanoengineering, an emerging category of technoscientific practice being established in part through the institutionalization of this department and its undergraduate degree program. I argue that this history and identity become articulated through an imaginary of nano worlds and nano dreams. Nano worlds signify the material possibilities of the nanoscale that are key to understanding the natural world and that are expected to enable technological innovation; the nano world connotes both the nanoscale world, and the macroscale world understood through nanoscale materiality. Nano dreams signify visions of future nanotechnologies that will benefit society and that inspire and

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Gallery Images From Isaac Asimov's Fantastic Voyage," Foresight Institute, http://www.foresight.org/Nanomedicine/Gallery/FanVoy/ , 2000; Farokhzad, Omid, and Robert Langer. "Small Is Fantastic: Exciting Times for Nanomedicine." The Economist/ From The World in 2013 Print Edition (2012), http://www.economist.com/news/21566438-exciting-times-nanomedicine-small-fantastic , 2012; Christina T. Loguidice, "Nanotech in 2009: A Fantastic Voyage," HPCLive, www.hcplive.com/publications/oncology-live/2009/may2009/ON_nanotech_in_2009 , 2009; Wyss Institute, "A Fantastic Voyage through the Future of Nanomedicine," http://wyss.harvard.edu/viewpage/476/ ; Ray Kurzweil and Terry Grossman, Fantastic Voyage : Live Long Enough to Live Forever, (Emmaus, Pa.: Rodale ; Distributed to the trade by Holtzbrinck Publishers, 2004).

For analysis of, see Brigitte Nerlich, "Powered by Imagination: Nanobots at the Science Photo Library," Science as Culture 17:3 (2008): 269-92; Kathryn D. de Ridder-Vignone and Michael Lynch, "Images and Imaginations: An Exploration of Nanotechnology Image Galleries." Leonardo 45:5 (November 5, 2012): 447-54; Zach Horton, "Collapsing Scale: Nanotechnology and Geoengineering as Speculative Media," in Shaping Emerging Technologies. Governance, Innovation, Discourse, edited by Kornelia Konrad, Christopher Coenen, A.B. Dijkstra, Colin Milburn and Harro van Lente: IOP Press, 2015.

motivate nanoengineers in their career trajectories. This imaginary ties common nanotechnologies on the market today—like antibacterial socks, nanosilver lined baby bottles, zinc oxide sunscreens, and chocolate—to the so-called nanotechnologies of the past such as the 4th century Lycurgus cup of Alexandria and the stained glass of Medieval cathedrals, each of which are now understood to take advantage of nanoscale properties and behaviors. It distinguishes between and merges nature and man as it reimagines the natural world in terms of nature's nanotechnological creations—including geckoes, butterfly wings, and plankton—and figures man's creations as biomimetic analogs.

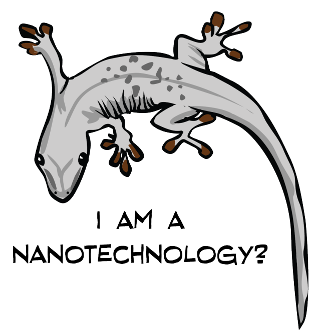

Illustration 30 Gecko. Many geckos have nanoscale structures in their feet that enable adhesion.

At the same time, this imaginary connects today's relatively incremental nanotechnologies to the promises of future revolutions in biomedicine, energy, information technology, and new materials. As it aspires to the complete and precise control and manipulation of matter on the atomic scale, it articulates "nano" as at once ordinary and extraordinary and defines it in the universal terms of innovation for the benefit of society.

Examining how cultural objects like *Fantastic Voyage* are taken up in epistemic communities is important for understanding the ways that a disciplinary program[3] constitutes a set of sociotechnical practices. These practices, while not determining, are constraining and productive of particular ways of knowing, imagining, and making the world, as well as understanding one's place within it. Additionally, such cultural objects can be assessed for opportunities to engender critical practice. By juxtaposing an ethnographically informed analysis of how the film is taken up in this pedagogical space with a close reading of the film itself, I attend to how the film becomes enrolled in fashioning a particular narrative for a nascent field, as well as to what gets excluded from this narrative. Drawing on the concept of constitutive exclusions,[4] I argue that the department's inclusions *and* exclusions of particular aspects of the film from its representation are constitutive of the history and identity it is trying to create. Specifically, it is a history of technological progress obtained by going smaller, and an identity that is intrinsically good in its pursuit of societal benefit.

The material for this chapter is primarily based on repeated observation of two introductory required nanoengineering courses and analysis of the corresponding lecture

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3. Timothy Lenoir, *Instituting Science : The Cultural Production of Scientific Disciplines*, Stanford, Calif.: Stanford University Press, 1997. Lenoir defines a disciplinary program as a local, contingent formation, in contrast to a discipline in the abstract.

4. Karen Michelle Barad, *Meeting the Universe Halfway : Quantum Physics and the Entanglement of Matter and Meaning*, Durham: Duke University Press, 2007; Sharon Traweek, *Beamtimes and Lifetimes : The World of High Energy Physicists*, Cambridge, Mass.: Harvard University Press, 1988. I am drawing on Barad's articulation of constitutive exclusions, which elaborates on Judith Butler's analysis of the limits of discourse, which in turn draws on Foucault's analysis of the effects of regulatory practices (Barad, 2007: 63). This refers to the "constitutive effects of…exclusions" (*ibid*, 58). That is, what is excluded is necessarily constitutive of what is included; the boundaries drawn around what is included presumes an outside. I am also influenced by Traweek's attention in her study of physicists to what is left out of the commonsense view of the world.

slides, interpretive analysis of *Fantastic Voyage*, and interviews with the chair, faculty, and students.[5] My analysis of the film as it is taken up in the department is particularly inspired by feminist science studies and cultural studies contributions that have been adept at examining the inseparability of science and culture,[6] and to feminist theory that draws attention to the constitutive nature of exclusions.[7] While it is common in science & technology studies (STS) to look at science *as* culture, it is less common to take cultural production and appropriation seriously, particularly when it occurs *within* epistemic communities.[8] In the following, I attempt to do that.

***Fantastic Voyage* and the Institutionalization of Nanoengineering**

Common descriptions of *Fantastic Voyage* depict a film that shows miniaturized technologies (humans in a submarine that are together shrunken down to the microscale)

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5. The human subjects protocol for this study was initially approved by the UC San Diego Human Research Protections Program on November 3, 2010 (101734).

6. See Barad, *Meeting the Universe*; Haraway, *Primate Visions*; Valerie Hartouni, *Cultural Conceptions : On Reproductive Technologies and the Remaking of Life*, Minneapolis: University of Minnesota Press (1997); Katherine Hayles and Los Angeles County Museum of Art, *Nanoculture : Implications of the New Technoscience*, Bristol, UK; Portland, OR: Intellect Books (2004); Nerlich, “Powered by Imagination”; Milburn, *Nanovision* ; and Traweek *Beamtimes and Lifetimes*.

7. See Barad, *Meeting the Universe Halfway*; Judith Butler, *Bodies That Matter : On the Discursive Limits of "Sex"*, (New York: Routledge,1993).

My work here is also grounded in science & technology studies (STS) approaches to scientific disciplinary formation, epistemic communities, and science fiction. These overlap with feminist science studies and cultural studies. See Donna Haraway, *Primate Visions : Gender, Race, and Nature in the World of Modern Science*, New York: Routledge, 1989; Karin Knorr-Cetina, *Epistemic Cultures : How the Sciences Make Knowledge*, Cambridge, Mass.: Harvard University Press, 1999; Lenoir, *Instituting Science*; Colin Milburn, *Nanovision : Engineering the Future*, Durham: Duke University Press, 2008; Steven Shapin, *The Scientific Life : A Moral History of a Late Modern Vocation*, Chicago: University of Chicago Press, 2008; Traweek, *Beamtimes and Lifetimes*. Each of these works have drawn on feminist and cultural studies theory as well as STS to examine science as cultural practice.

8. Examples of work that do engage culture within epistemic cultures and that inform the present work include Haraway, *Primate Visions*; Milburn *Nanovision*; and Stefan Helmreich, *Silicon Second Nature : Culturing Artificial Life in a Digital World*, (Berkeley: University of California Press, 1998.

entering the body of a human patient for the medical purpose of saving his life. This common description is what is primarily invoked in my site. While I will provide a more in-depth analysis of the film in my discussion of constitutive exclusions, here I want to first contextualize my ethnographic analysis with a brief plot summary.

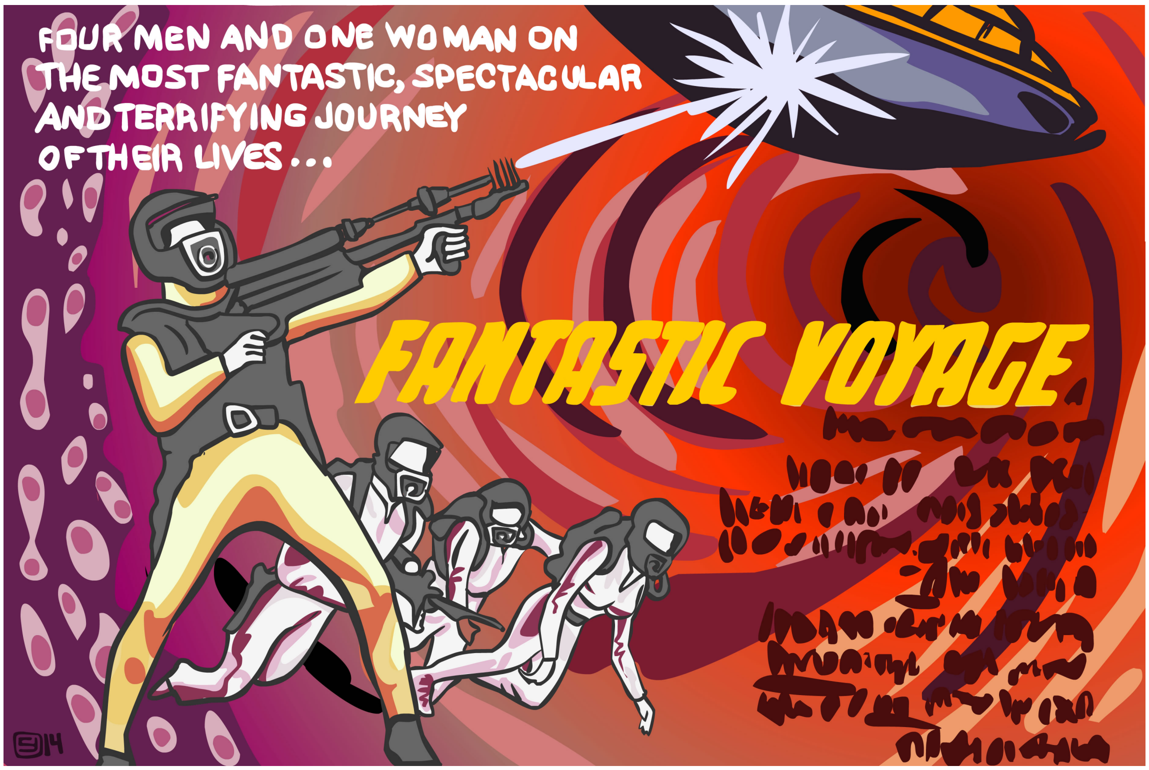

Illustration 31 *Fantastic Voyage* poster.

A Cold War film, *Fantastic Voyage* tells the story of a U.S. military mission to save the life of a Russian defector who holds top secret knowledge related to miniaturization technologies. Upon his arrival in the United States, an assassination attempt leaves the defector unconscious with a life-threatening blood clot in his brain. The U.S. military mission brings together a team of military and medical personnel who are miniaturized in a submarine and sent inside the defector's bloodstream. Their mission is to locate and clear the blood clot in order to save his life with the purpose of ultimately obtaining his technical knowledge. Specifically, this is knowledge that would allow the U.S. to shrink an entire army down to the size of a bottle cap, send it behind enemy lines, and control its resumption to normal size. The team encounters multiple challenges that stem from social, political, technological, and environmental factors, and the personnel barely escape from his body with their lives. The film ends with the crew's survival but without any indication that the mission has been a success.

Fantastic Voyage is invoked in this nanoengineering department to establish a disciplinary history and identity for a new kind of scientist-engineer-innovator: the nanoengineer. The founders of this department describe a kindred connection to the film. To some extent, it catalyzed their creation of the department. According to one of the founding members, when he and two other faculty members discovered they had all been incredibly moved and professionally inspired by the film as young people, they decided they needed to create a new disciplinary space to enable the kind of innovation that would be necessary to realize the film's vision.[9] In fact, one of their first hires was someone whom they perceived was doing research that realized the vision of *Fantastic Voyage*. Yet while the film serves as history, inspiration, and promise for the nanoengineers, it would not necessarily be understood by them as constitutive of their field or identity. This is in part because they understand nanoengineering as already existing in nature, only recently made available to human ingenuity through the vision of Nobel Laureate Richard Feynman and subsequent technological instrumentation. From this perspective, it would be impossible to say that a cultural object like a film could help

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9. He also indicated that establishing a new department would enable them to hire new, outside faculty rather than just cross-listing existing faculty. He identified this as important to creating something truly interdisciplinary. This discussion occurred over an informal lunch meeting on October 11, 2012.

to produce the field. This may explain why despite the fact that the film is invoked explicitly and implicitly in multiple lectures by multiple faculty and is described and compared to current research, faculty do not actually show it in class; instead they encourage students to watch it on their own. This different perspective regarding the role of the film as representational and inspirational but not constitutive speaks to disciplinary differences between nanoengineers and myself as an ethnographer coming from communication, STS, and cultural studies. Yet their use of the film as part of their disciplinary and departmental history makes agreement on its import, if not the precise nature of its import, possible. I will return to this in my discussion of potential interventions. But first I will show how the film, as it is taken up by this epistemic community, concretizes a disciplinary history for nanoengineering, connects prophetic imagination to popular imagination, defines a particular temporal dynamic of innovation for the field, and constructs a moral economy centered around an intrinsically ethical nanoengineer. I will show how its placement on an historical timeline as it is introduced to students begins to establish disciplinary history and to connect prophetic and popular imagination, though my evidence will also begin to elucidate the kind of exclusions that I attend to as I analyze what is included.

There are different timelines for nanotechnology in circulation, each organized in a linear trajectory around nanoscale research and development. These different timelines attempt to consolidate a range of practices and present nanoengineering and nanotechnology as inevitable. In one nanotechnology textbook used in the curriculum in my site, “Nature” is designated as “the first nanotechnologist” and nano is said to go back “billions of years if nature is included.”[10] Some timelines also go into the future.

FORESIGHT
INSTITUTE
ADVANCING BENEFICIAL NANOTECHNOLOGY
HTTP://WWW.FORESIGHT.ORG/

Illustration 32 Foresight Institute. One of its founders was Eric Drexler, engineer and author of *Engines of Creation*, a 1986 book that popularized nanotechnology and molecular engineering.

For example, the Foresight Institute, a nanotechnology advocacy think tank, describes first through fourth generations of nanotechnology, explaining that the first generation is out on the market in the form of common consumer products, the second is in the lab, the third is in simulation, and the fourth generation will be realized when complete control of the material world at the atomic scale is achieved.[11] A poster prominently displayed in my

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10. Gabor Hornyak, Introduction to Nanoscience, (Boca Raton: CRC Press, 2008): 5.

11. http://www.foresight.org/nano/whatismm.html.

research site displays a trajectory for nanotechnology that begins with the atomic bomb and ends in 2050 with space travel and artificial intelligence.[12]

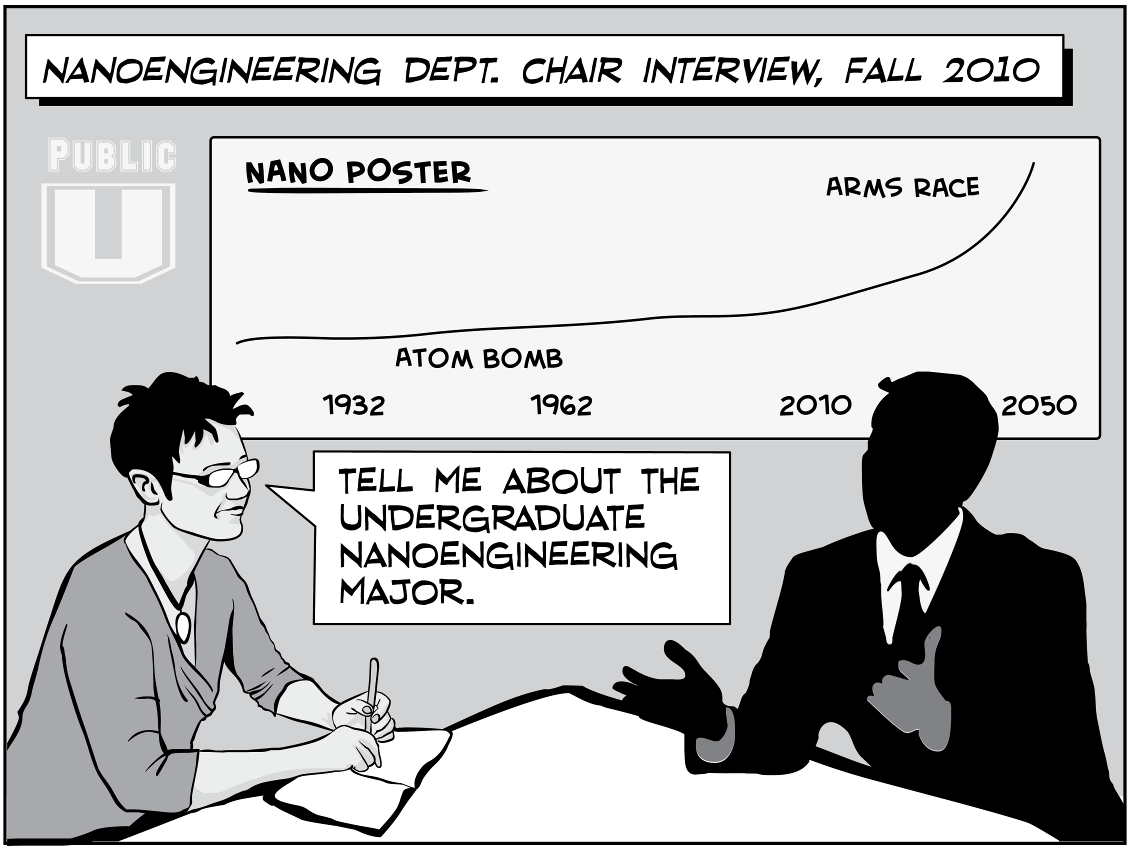

Illustration 33 Nanoposter backdrop.

In doing so, it suggests that these future events are inevitable, as concrete as the historical events on the same timeline. And in the timeline published on the website of the NNI,

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12. I originally encountered the poster in the department on the wall outside the chair's office when I interviewed him. He indicated that he had placed it there and that he loves this poster. I later encountered the poster in several other locations as well. The poster was designed by a graphic designer named Alexander Grigorovich-Barsky, who solicited input from nanotechnologists. He researched the topic of nanotechnology independently and engaged with nanoengineers as part of that research (from private email communication, February 28, 2011). A brief online conversation in 2006 appeared on the Foresight Institute's website here: http://www.foresight.org/nanodot/?p=2251.

nanotechnology begins in the 4th century with the Lycurgus cup, a piece of Alexandrian glass that changes color depending on the angle of light due to the presence of nanoscale silver and gold particles. In the modern era, the NNI timeline includes the coining of the term “molecular engineering” in 1956, Richard Feynman’s speech “There’s Plenty of Room at the Bottom” in 1959 (hereafter *Plenty of Room*),[13] Gordon Moore’s articulation of “Moore’s Law” in 1966, and Norio Taniguchi’s coining of the term “nanotechnology” in 1974.[14] These examples suggest both a widespread perception among nano enthusiasts that a timeline is necessary to stabilize nanoengineering, and that no particular timeline has yet obtained exclusive authority. The timeline presented by the nanoengineering department in an introductory required nanoengineering course—which I’ll refer to as Intro I—largely parallels the NNI account, but it begins with the 1959 speech by Feynman and follows with the 1966 film *Fantastic Voyage*. Situated between Feynman’s speech and Moore’s Law, the film is established as an important element in the history of nanoengineering, particularly for the department’s founders.

Intro I is taught with the stated objective of introducing nanoengineering majors to the field and degree program and generating enthusiasm for nanoengineering. The department’s formal proposal for an undergraduate major states: “With the large number

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13. Richard Feynman, "There's Plenty of Room at the Bottom" in *Engineering and Science* 23:5 (1960): 22-36.

14. http://nano.gov/timeline. The NNI was established in 2000 under President Clinton.

of basic science requirements, we must provide a mechanism to motivate the students and retain their interest."[15] It additionally describes four objectives for the class:

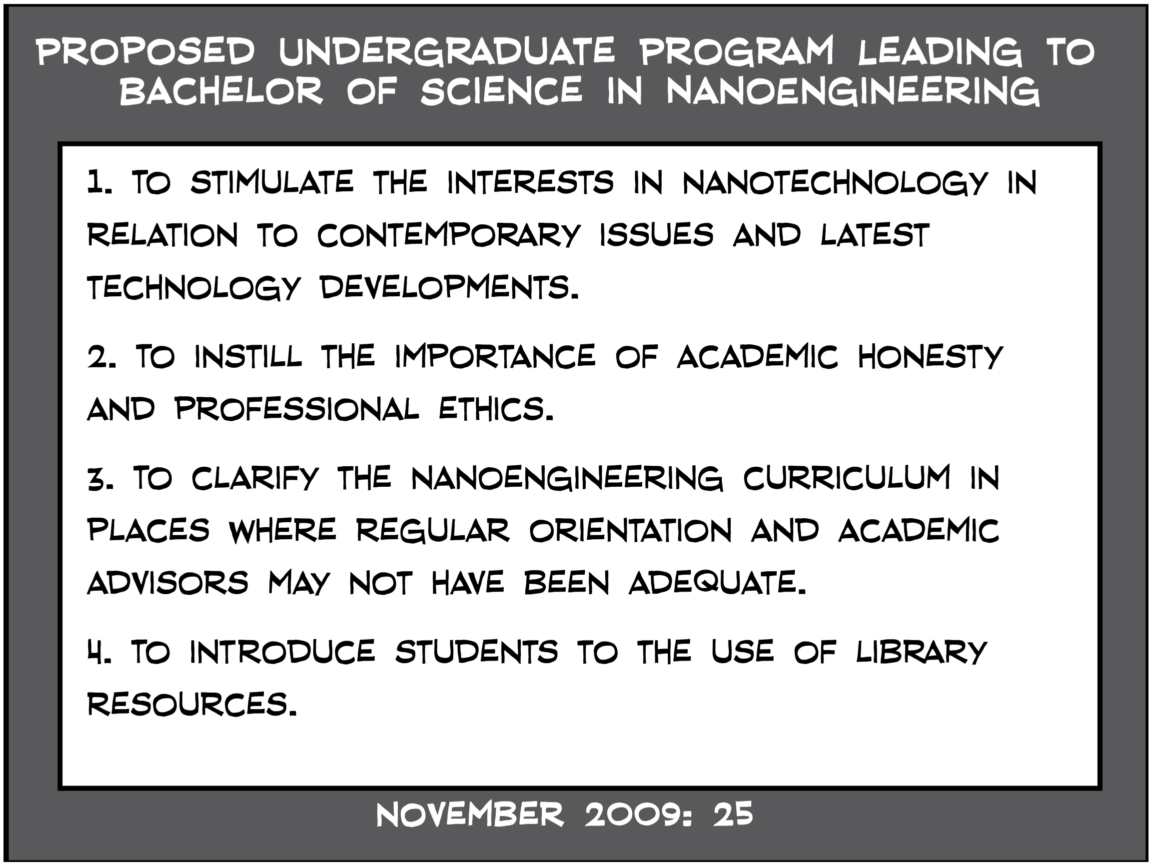

Illustration 34 Intro I course objectives. 1) To stimulate the interests in nanotechnology in relation to contemporary issues and latest technology developments. 2) To instill the importance of academic honesty and professional ethics. 3) To clarify the nanoengineering curriculum in places where regular orientation and academic advisors may not have been adequate. 4) To introduce students to the use of library resources.[16]

Establishing a disciplinary or professional identity for nanoengineering is not an explicitly stated objective. Yet through the practices of stimulating interest, motivating students, and covering the stated course topics (such as "what nanoengineering is all

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15. "Proposed Undergraduate Program Leading to Bachelor of Science in NanoEngineering," Prepared (2009): 12. An unpublished document provided to me by the Chair of the department.

16. Ibid., 25.

about," "examples of nanotechnology topics, and career opportunities," and "the nanoengineering faculty and their research interests,") an identity is articulated.[17] I will return to a discussion regarding the course objective of professional ethics, which is only implicitly addressed in this class through references to clinical trials for biotechnology applications.

The professor opens the class with a purpose:

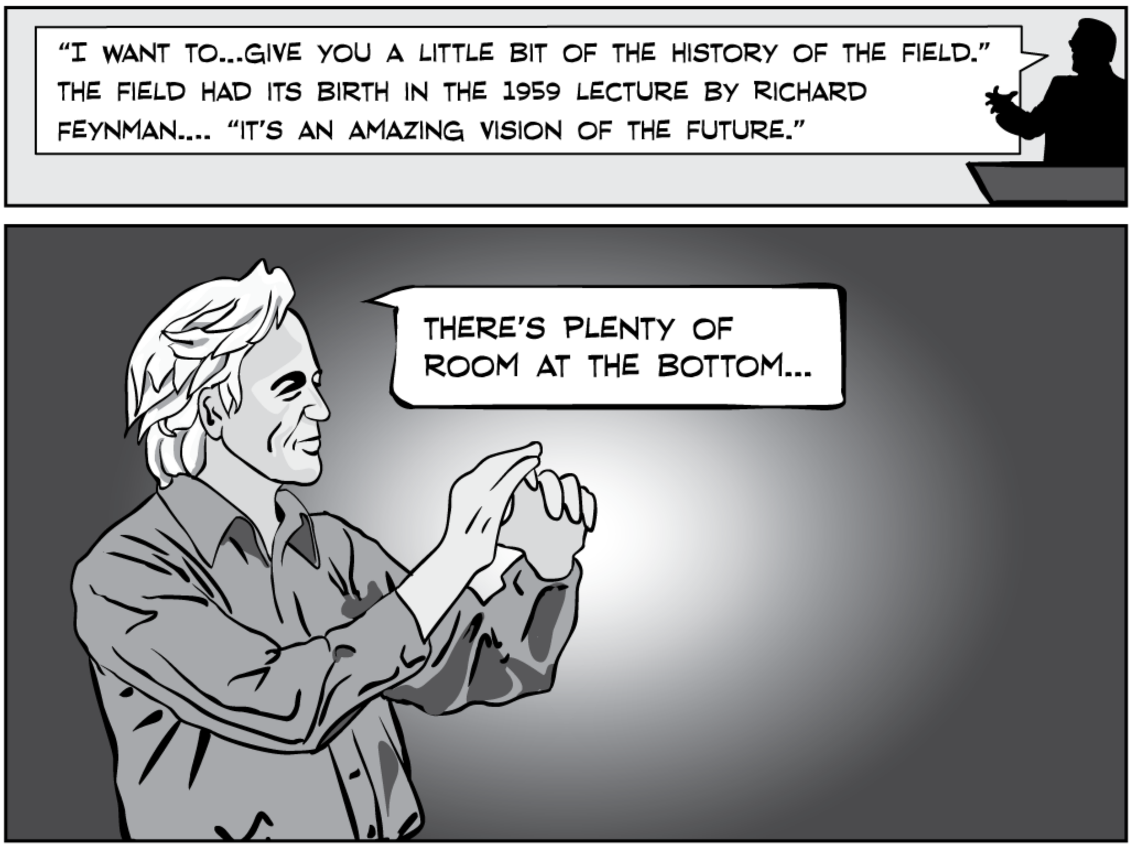

Illustration 35 Richard Feynman, 1959. The professor says, "I want to…give you a little bit of the history of the field."[18]

17. Ibid., 25.

18. NanoEngineering Professor, Intro I, 2011. Observed and transcribed by author.

Describing the talk as "… an amazing vision of the future," he says, "I want to show you what the vision was, and where we are currently with some of those things." His introduction grounds all subsequent events of the field in the vision of a highly respected father figure.[19] In a nanotechnology textbook used in the curriculum in a later class, Feynman is referred to as the "prescient physicist" who delivered his "prophetic" talk in 1959,[20] and similar rhetoric about Feynman pervades the department and curriculum. Students are encouraged to listen to the TEDx talk "Feynman's Vision: The Next 50 Years," hosted by the California Institute of Technology, in order to "understand the vision of the field." In it, IBM physicist Don Eigler presents reflections on Feynman that have an almost hagiographic tone.[21]

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19. Milburn, *Nanovision*; Andreas Junk and Falk Riess, "From an Idea to a Vision: There's Plenty of Room at the Bottom," American Journal of Physics 74:9 (2006): 825-30). Milburn argues that Feynman's status as a Nobel Prize winning physicist makes him the ideal father figure in terms of conveying authority to an emerging industry. And Junk and Reiss argue that not only are scientists who cite *Plenty of Room* essentially doing it for their own benefit, but that they miss the mark in that Feynman was more interested in biological machines and that he would not have taken credit for founding theoretical nanoscience. In this department, while both arguments may be true, I would argue that invoking Feynman is not done in a cynical way. Moreover, there is a huge emphasis in this department on biomimesis and biomedical machines, so in that sense, it is not discontinuous with Feynman's interest as Junk and Reiss interpret it. In fact, the Professor said the following in his January 5, 2011 lecture in Intro 1, explaining Feynman's talk: "He [Feynman] also talked about the fact that there'd be a unique connection between this ability to produce small scale materials, and biological systems. And this is perhaps where nano will have its initial biggest impact, is because you're dealing with materials that have functionality, and makes, you make them small enough so that they can fit inside cells. We can now create materials that interact with specific functions inside cells. That allows us to produce unique kinds of cures. Okay? So in the area of biology and medicine, nano is having already a significant impact, and nearly a third of our faculty work in that area."

20. Ben Rogers, Jesse Adams, and Sumita Pennathur, *Nanotechnology : Understanding Small Systems*, Mechanical Engineering Series, Boca Raton, FL: CRC Press, 2008, 13.

21. https://www.ted.com/tedx/events/752; Chris Toumey, "Reading Feynman into Nanotechnology: A Text for a New Science." *Techne* 12, 3, 2008, 133-68. Eigler said that one night after he first used a scanning tunneling microscope to move an atom, he was sitting in his office, when the hairs on the back of his neck stood up. He described feeling like a ghost was there, and he realized that Feynman had talked about manipulating atoms in his famous 1959 paper. Eigler went on in his TEDx talk to read excerpts of that paper, and to marvel at the amazing prescience of it, then to borrow its form to project his own work into the future.

The professor alternates between quoting from Feynman's imaginings of future technological capabilities and subsequent historical moments in the development of the field, including present activities in the nanoengineering department. This dialogical movement creates a particular order to the emergence of nanoengineering, enacting a logic that pairs idealization with subsequent materialization. That is, it suggests that the act of articulating an ideal vision is at least in part constitutive of what comes to be. I will return to this momentarily in my discussion of the nano dream, but here I want to emphasize that situating the film—one of these historical moments on the timeline—within Feynman's utterances works to demonstrate a progressive concretization of vision into reality (from word, to film, to instrumentation, to field).

Toumey argues that *Plenty of Room* is read retrospectively into the history of nanoengineering but did not have any direct influence over earlier developers of nanotechnology-related instrumentation and practices. He therefore contests its status as the origin of nanotechnology. While his argument is convincing, when looking at nanoengineering as a field only currently being consolidated as such, it is just as important to look at how it is working now than at how it did or did not specifically influence "important scientific developments in nanotechnology" in the 1980s (133). Indeed, arguably it is only retrospectively that we can understand such developments as constituting nanotechnology developments. So while nanotechnology as a field may not have begun with Feynman's talk in 1959, and there may not be a single and direct line from Feynman's talk to the STM to nanotechnology as a field, it does figure into the consolidation of nano as a distinct disciplinary and professional identity being consolidated in the 2000s. For one of the first generations of nanoengineers to identify as nanoengineers, Feynman's talk works as an origin story, however historically inaccurate. In this sense its status as a true or false origin story is less interesting than the work it does as an origin story in the formation of a disciplinary program.

Illustration 36 Vision to reality. I position the nanoengineer on the left, however, to emphasize that the historical vision of the future, embodied by Feynman, is articulated from the perspective of the contemporary nanoengineer.

This dialogical movement additionally connects Feynman's vision to the popular imagination of nanoengineering depicted in a Hollywood motion picture and to the professional vision of the nanoengineer.

Just prior to mentioning the film, the professor says:

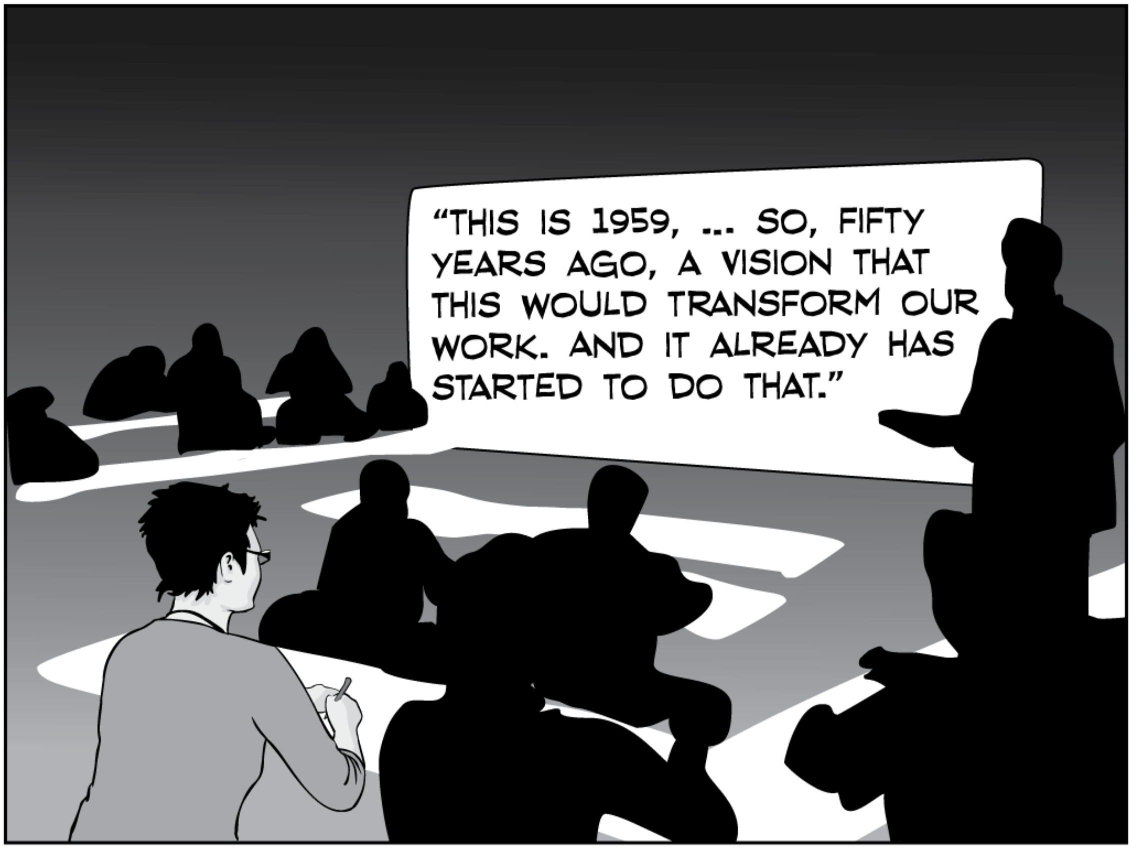

Illustration 37 The vision. "This is 1959, … so, fifty years ago, [there was] a vision that this would transform our work. And it already has started to do that."[22]

He continues: "What [Feynman is] talking about is manipulating control of materials on this very small scale, what we have coined as 'nanoengineering', and this is sort of our view as to where that field is going." Note that what he highlights from Feynman's description is "manipulating control of materials on this very small scale," a recurring theme in nanoengineering's material and discursive practices and a central theme in *Fantastic Voyage*. Indeed, this phrase serves to define the field, as "what we have coined as 'nanoengineering'." While the aspiration of material control is hardly new or unique to

22. NanoEngineering Professor, Intro I, 2011.

nanoengineering, its realization on the nanoscale and the uniqueness of the nanoscale is key to consolidating nanoengineering as a field.

Then he briefly contextualizes the film, followed by a short description of the plot:

> In 1966 Hollywood kind of had it's first go at what we sort of view as sort of [a] microtechnology field. This was the movie *Fantastic Voyage*…. When I was young, *Fantastic Voyage* was the state of the art, the most futuristic movie that had been created. It seems trivial and simpleminded now, but at the time it was amazing….

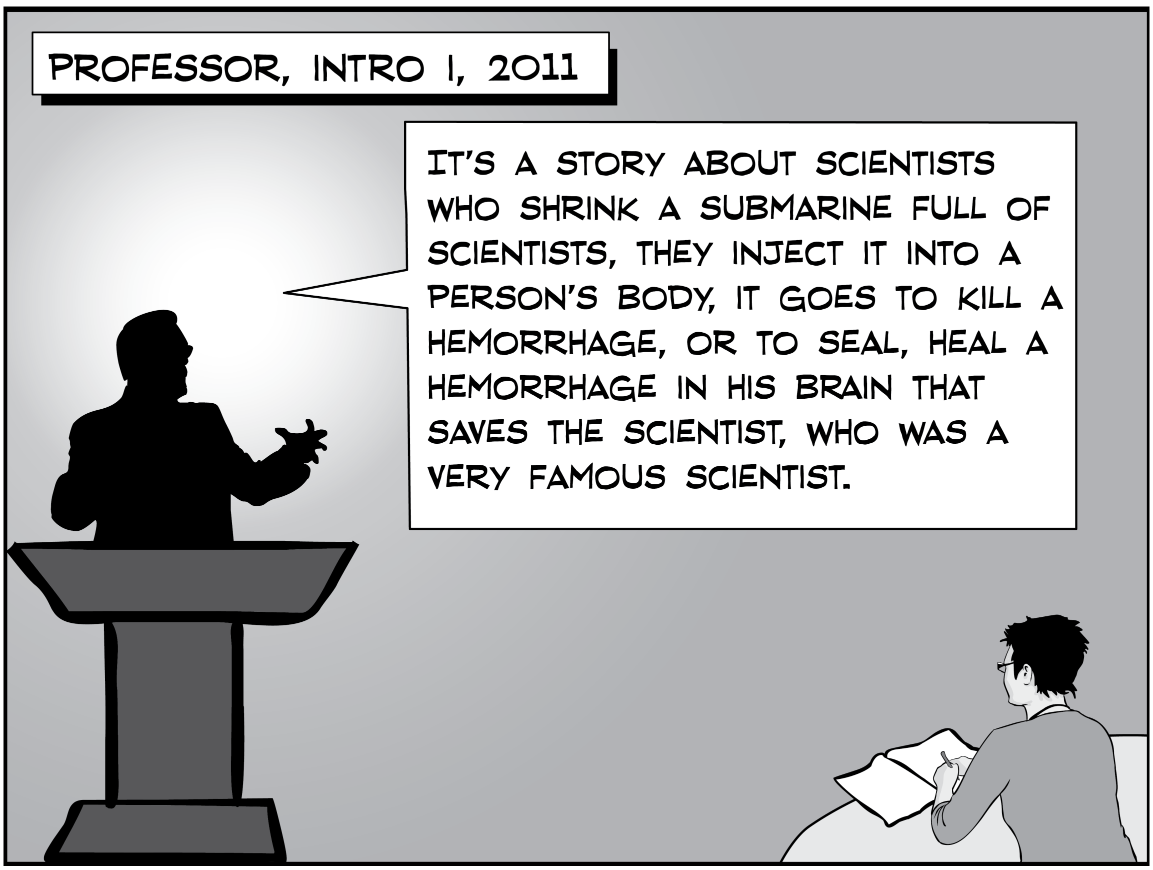

Illustration 38 *Fantastic Voyage* plot summary. "It's a story about scientists who shrink a submarine full of scientists, they inject it into a person's body, it goes to kill a hemorrhage, or to seal, heal a hemorrhage in his brain that saves the scientist, who was a very famous scientist."

And he concludes that "…it was a very visionary view of the field." The vision is described as futuristic and amazing, establishing the magnitude of realizing such a vision and demonstrating that these visions are not merely incremental ones. His plot description also suggests that the only people involved are scientists—scientists shrink a sub full of scientists to save the life of a scientist—and implies that the reason to do this is because the ailing scientist is famous.[23] By describing the plot as revolving around scientists saving someone's life, the mission is framed as medical, and therefore ethical (good), universal and apolitical. That is, by narrating the goal of the mission as saving a man's life and as including only scientists (figures that have an aura of political neutrality), he implicitly suggests that the film is about science and medicine rather than weapons and war, and that it has no particular geopolitical location. To be clear, I'm making a claim about the productive work of this framing, not about his intentions. Indeed framing the story as a medical story if the goal is to connect it to current nanomedicine research seems like a straightforward choice but, as I will show, it has consequences. The verbal slip-up, when the professor initially uses the word "kill" and then corrects himself to say "heal," is the kind of error that can happen when talking extemporaneously, but I note it due to the ambiguity between healing and killing that takes place in the film, which I'll revisit in my analysis of constitutive exclusions.

After another connection between *Plenty of Room* and later research, the professor continues:

> So, moving forward. 1996… [the] nanomedicine field took on a different view, so Hollywood became a little nicer to us, we didn't have to be

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23. Over lunch, I mentioned to the professor that I had watched the film, and was surprised to realize that it is a Cold War film about shrinking an army to send it over to the other side. I asked him when he last saw it, and he replied that he watches it all the time because he frequently uses it in his talks. It is reasonable to assume then that the omissions in his plot summary regarding the Cold War and weapons aspects cannot be attributed to relying on an old memory or a secondary source. Informal discussion with NanoEngineering professor and founding member, October 11, 2012.

> shrunk down, we developed this way to build these miniature robot machines that we put into the bloodstream. And…we are closer to this vision than you might imagine. We have one of our faculty members who builds nanomotors, nanobots, that create self locomotion, and have learned how to pick up blood particles [deliver them in?] a fluid system, deposit them elsewhere, so what we see here as 1966 Hollywood is already being done, now, not in the bloodstream yet, but in blood and in urine and in other bodily fluids, so the jump from where we're at to the vision a few years back, it's not all science fiction. Okay? Unfortunately, nano is often portrayed as science fiction. If you haven't read *Prey*, it's a great book. It happens to be based on a lot of actual science, but it is a great book.[24]

In the beginning of this quote, the phrase, "Hollywood became a little nicer to us, we didn't have to be shrunk down," suggests that the collapse of the human and the technological in *Fantastic Voyage*, represented by humans in a submarine who together become the technological apparatus inserted into a human body, is merely an aspect of 1966 Hollywood being "trivial" and "simpleminded." The reality of nanomedicine is framed as more sophisticated: "…we didn't have to be shrunk down, we developed…miniature robot machines…" So while the film shows human and nonhuman elements inextricably intertwined (a portrayal that STS scholars might champion), the professor reinforces their inherent separability, distancing the scientific and engineering practices of nanoengineering from the film's representation of human beings as microtechnologies. While a part of the film is rejected, another part of the film is taken up to illustrate that the vision of controlling and manipulating matter on a small scale is being realized in the current work of a professor in the department "…who builds nanomotors, nanobots, that create self locomotion, and have learned how to pick up blood

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24. The professor is referring to the science fiction novel *Prey* by Michael Crichton, *Prey*, 1st ed, New York: HarperCollins, 2002.

particles." The film serves as a pivot between Feynman's vision and current research in the department: "…what we see here as 1966 Hollywood is already being done, now." This reference back to the film in conjunction with contemporary nanomedicine research in the department emphasizes that a transformation has occurred, from a vision to its realization, blurring what constitutes science fiction and what constitutes reality.[25] Nano is *not* science fiction, but the science fiction novel *Prey* has a lot of "actual science."

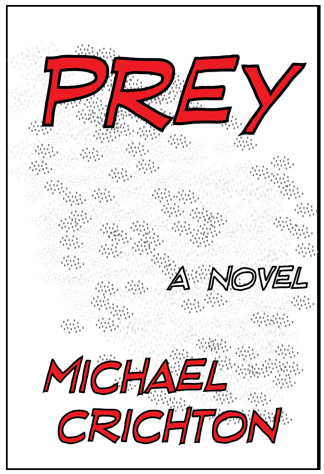

Illustration 39 Michael Crichton's *Prey* came out in 2002 and imagined a "gray goo" of swarming nanobots.

The prophetic vision of Feynman becomes science fiction first in the film but as it materializes into reality through the labor of the nanoengineer, it becomes nano. That is, innovation materializes in a linear progression from fiction into fact, from vision into reality, such that fantastic visions can be materialized, potentially within the timeframe of a nanoengineer's lifetime. This isn't to suggest that the professor or other faculty present this as an easy or magical process; research is presented as labor-intensive and

25. Milburn, *Nanovision.* This exemplifies the kind of mutual constitution of science and science fiction that Colin Milburn terms "nanovision."

challenging. Rather, it speaks to the possibilities and hopes of creating something totally novel.[26] I highlight it in part because my approach to intervention, which I will elaborate later, relies on finding common ground between scientists, engineers, and people in the social sciences and humanities. Here, the inclusion of fiction and vision speak to the multifaceted processes of knowing and making that are both material and discursive, and therefore indexes a way in to multidisciplinary dialogue.

In another introductory nano course, which I will refer to as Intro II, a full-credit course students take in their second year, another professor invokes the film to define the "nano dream" as that which should guide the dynamic between vision and reality. The nano dream is a vision of a future nanotechnology that will benefit society and guide one's present research and career trajectory. Like the professor of Intro I, this professor starts with *Plenty of Room* and then tells a similar version of the plot. Accompanying his description are slides showing images from the movie:

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26. This sense of possibility is framed in the mission statement of the department using the following quote from Theodore von Kármám: "The scientist describes what is, the engineer creates what never was".

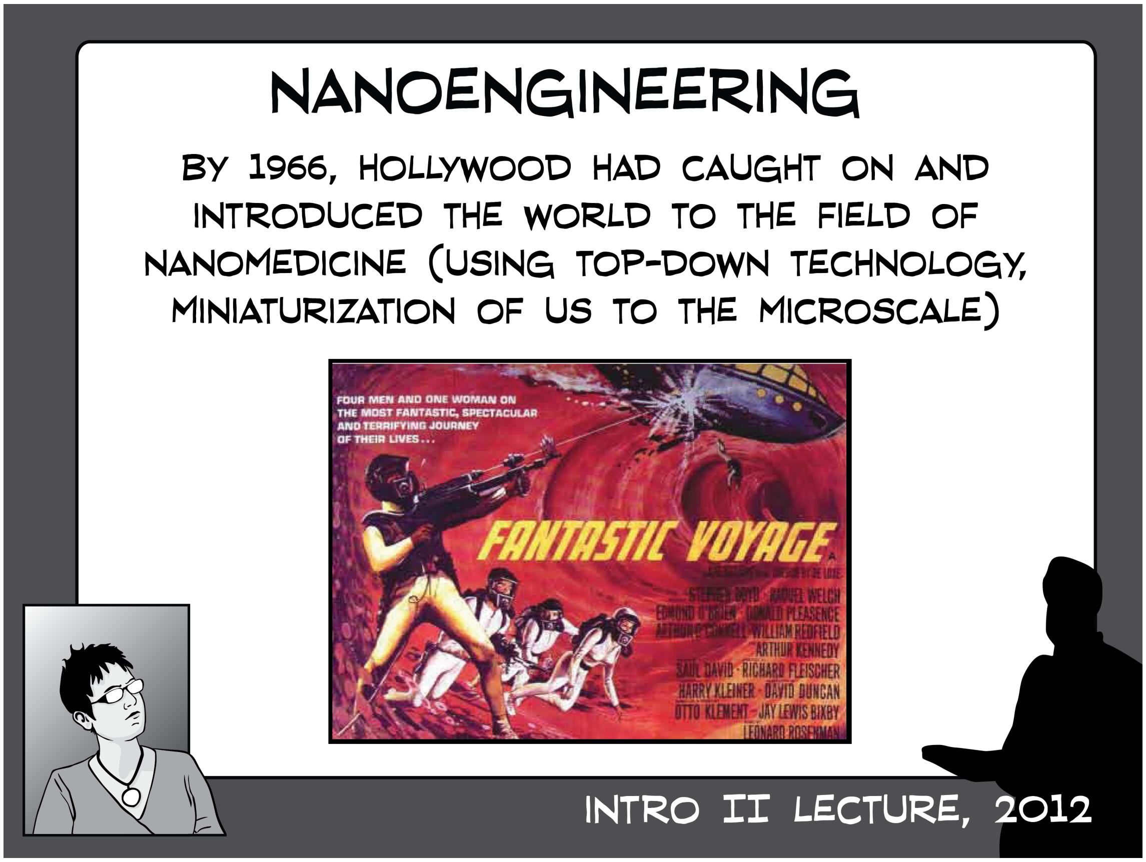

Illustration 40 Hollywood caught on. "By 1966, Hollywood had caught on and introduced the world to the field of nanomedicine."

Again, by situating the film after Feynman, the professor implicitly suggests that Hollywood is taking up Feynman's vision in its portrayal of a miniaturized medical technology, and he connects prophetic vision to popular imagination. He also suggests that the idea of nanomedicine existed in the 1960s, which correlates with a disciplinary history that begins in 1959.[27] He then shows that by the 1980s, there is a move "From

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27. As a feminist STS and communication scholar, this strikes me as inaccurate and anachronistic (is either Feynman or *Fantastic Voyage* actually referring to nanomedicine?). However, I acknowledge that my reaction to this speaks to disciplinary differences. From the perspective of the nanoengineer, the field exists prior to its institutionalization, as I described on page 8. Also, from this slide alone it is not clear whether he is referring to the idea of nanomedicine rather than nanomedicine itself. But, in conjunction with the subsequent slide which distinguishes between the 'nano-dream' and the 'reality' of nanomedicine, it seems clear that he is referring to the idea of it. Even if it wasn't called 'nanomedicine', I would agree

'Nano-dreams' to Reality," and in the context of reality he discusses nanomedicine. On the slide for nanomedicine, there are two pictures that again juxtapose vision and reality:

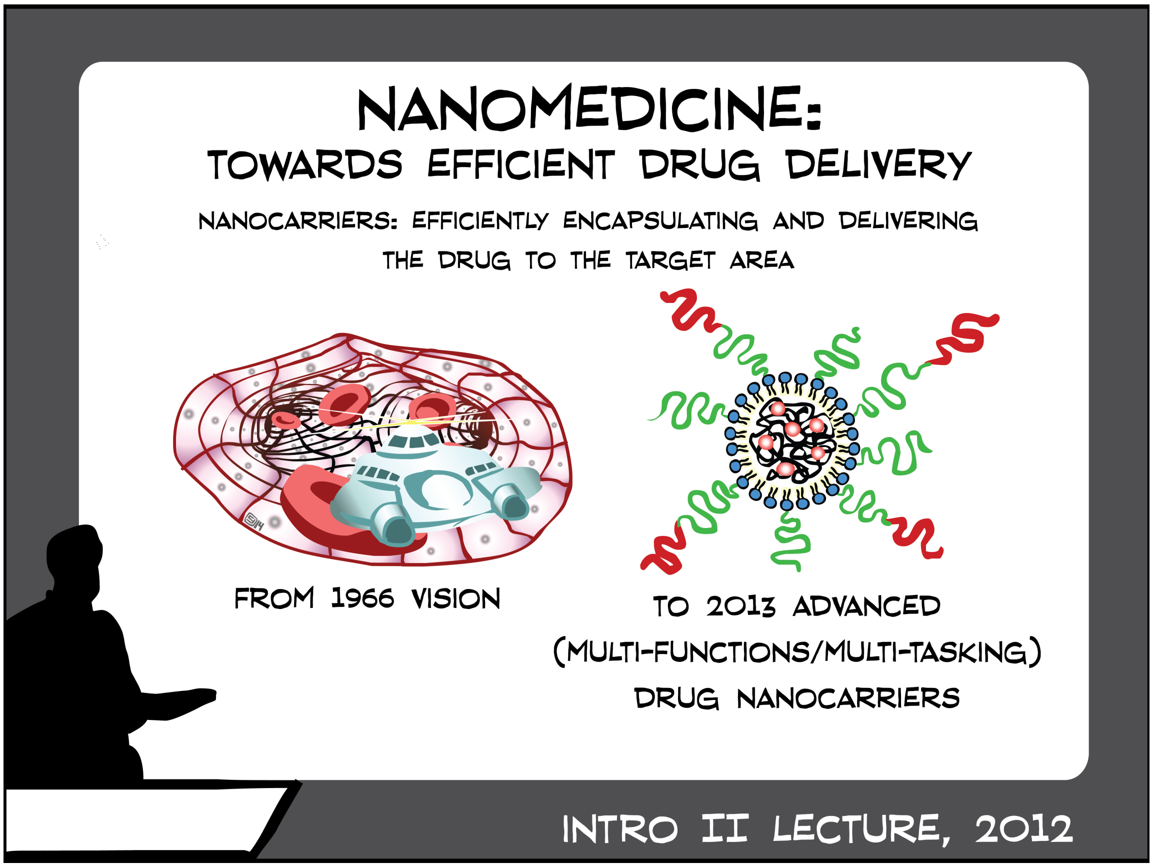

Illustration 41 Nanomedicine.

An implied theory of this lineage is as follows: first, the field as a material possibility and phenomenon is naturally occurring; the field is then articulated by Richard Feynman in 1959; a Hollywood science fiction film connects Feynman's vision to popular imagination, inspiring young people to go into science and engineering in order to realize the vision; gradually new developments in instrumentation begin to make nanoscale research and development humanly possible; and now, the field is being established at

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that the idea of small and targeted medical treatment is portrayed in the film, and that it is this idea that is central to current conceptions of nanomedicine. In this sense, then, I can find common ground.

places like UC San Diego, where this professor is teaching and is conducting nanomedicine research that, for him, realizes the vision of *Fantastic Voyage*.[28] According to this narrative, popular imagination embodied in a cultural object becomes personal, professional, and institutional imagination, and serves as a critical element in the materialization of nano—the field, the practitioner, and the technologies.

In a subsequent lecture, the professor again connects the film to the nano dream when he promises to "…talk about the *Fantastic Voyage*, about the dream." And he says,

> So we started with the *Fantastic Voyage*, this was the goal in 1966, to take a vehicle, to shrink it, to swim in the blood, can do the binding to a cancer cell, can do the imaging, can [deliver?] a therapeutic payload, can navigate in the blood, and can do the cancer therapy.[29]

Notice in this quote that there is a slippage from a description of the goal in 1966 (a goal that is read into the film) into the description of what the professor "can do" right now, which is itself merged with the promise of nanobot targeted drug delivery mechanisms that will fundamentally alter the treatment of cancer in the future; the nano dream collapses past, present, and future. The professor also reframes the *Fantastic Voyage* vision as a story about shrinking a vehicle rather than shrinking humans inside a vehicle, discarding the non/human apparatus represented in the film, just as the professor of Intro I did.

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28. See Cyrus Mody, *Instrumental Community : Probe Microscopy and the Path to Nanotechnology*, Cambridge, Mass, MIT Press, 2011 for an analysis of the mutual articulation of probe microscopy and nanotechnology.

29. NanoEngineering Professor, Intro II Lecture 2012, observed and transcribed by author.

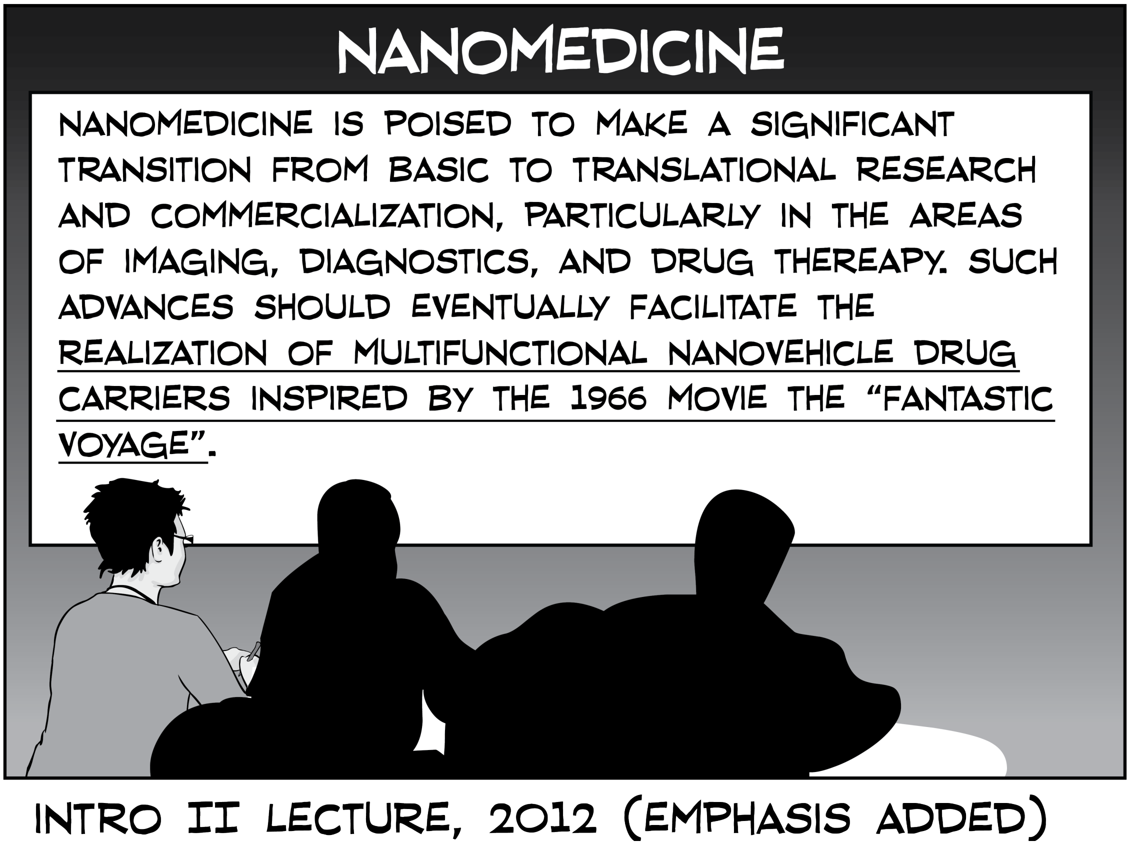

Illustration 42 Multifunctional nanovehicle drug carriers inspired by the 1966 movie.

Finally, the professor's main lecture on nanomedicine references the film, including a link to it so that students can watch it on their own. The last lecture slide concludes with an image of the film and the words, "Follow your nano dreams!" Recall that the nano dream itself is defined as a future beneficial nanotechnology that the nanoengineer endeavors to develop. This central message communicates to students that they too should call upon popular and personal imagination to pursue the research and development of nanotechnologies that will benefit society and that will serve as the ideal toward which they direct their life and work.

As I will expand upon momentarily, the refrain "follow your nano dreams" is important in the construction of how the moral economy of nanoengineering is constructed. Nanoengineering becomes delimited as an inherently ethical domain of practice, and the nanoengineer comes to understand her identity as one that is intrinsically good. That is, by translating "nano dream" into "benefit of society"—and here translation signifies both semiotic translation as well as the material and economic translation of research into products on the market (see Chapter 6)—nanoengineering comes to represent a disciplinary and professional identity that originates in Nature and that is guided and defined by its mission to benefit society.

However, this imperative for the nanoengineering student to follow her nano dream belies a tension between the individualist idea that the student should craft and then realize her own dream, and the realities of nanoengineering-related knowledge production that largely occurs in academic or industrial labs, where the academic labs are often working with industrial partners; in either location, the futures that can be pursued are those that are "investable" and agreed upon by multiple parties.[30] Additionally, as previously noted, the justification of the undergraduate degree program is to produce bachelors degrees who will become the workforce of this industry. That is, the majority of graduates are expected to become the relatively cheap labor force of industry, working according to the agendas set by their industrial employers. Whose dreams actually get materialized? The aspirational figure that informs this imperative is that of the entrepreneur. The promise is that each student has the potential to follow her own nano dream, including obtaining her own patent and creating her own company. This is made explicit on multiple occasions. For example, in one introductory nano course when the

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30. See Shapin, *The Scientific Life*, for a discussion of investable futures, or the idea that future visions must be able to attract investors.

professor describes the faculty in the department, he emphasizes their entrepreneurial nature:

> Our group also has started somewhere in the neighborhood of fifteen companies from the faculty itself, spinoffs. I've started a company that actually I'm not even involved with anymore, they commercially are selling products and generating revenue…. I'm actually involved in starting up another one right now….
>
> [He then describes how many companies different faculty members have started, including one who has started eight companies.]
>
> So … we are a department really committed to translational research…. we have a very very strong focus on being able to take what we do and turn it into a real industry…. we're very unique, down-to-earth, trying to get technology and science done in parallel.[31]

In describing how faculty start companies and spin-offs, the professor communicates that becoming an engineer-entrepreneur and realizing one's nano dream are both possible and desirable. I explore this theme in Chapter 5, where I consider how the institutional imperative to produce human capital manifests in the undergraduate curriculum in the form of entrepreneurialism.

Returning to these introductory lectures, we see the film invoked not only as a static element in the history of this new field—a point on the timeline—but as a material and discursive practice that is doing work toward the production of a nanoengineering identity. The professors construct a symmetric relationship between Feynman introducing nano to scientists, and Hollywood introducing nano to the public; these are functionally equivalent in discursive power. *Plenty of Room* and *Fantastic Voyage* are positioned as

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31. In Chapter 6 I argue that the trope of translational research unites the utopian horizon of nanoengineering, represented by the nano dream, with the utilitarian imperative to efficiently and effectively innovate and commercialize produces that will be used by people.

communicating amazing visions that have become realized in the labs of this new department, narrativizing a dream-to-reality progression.

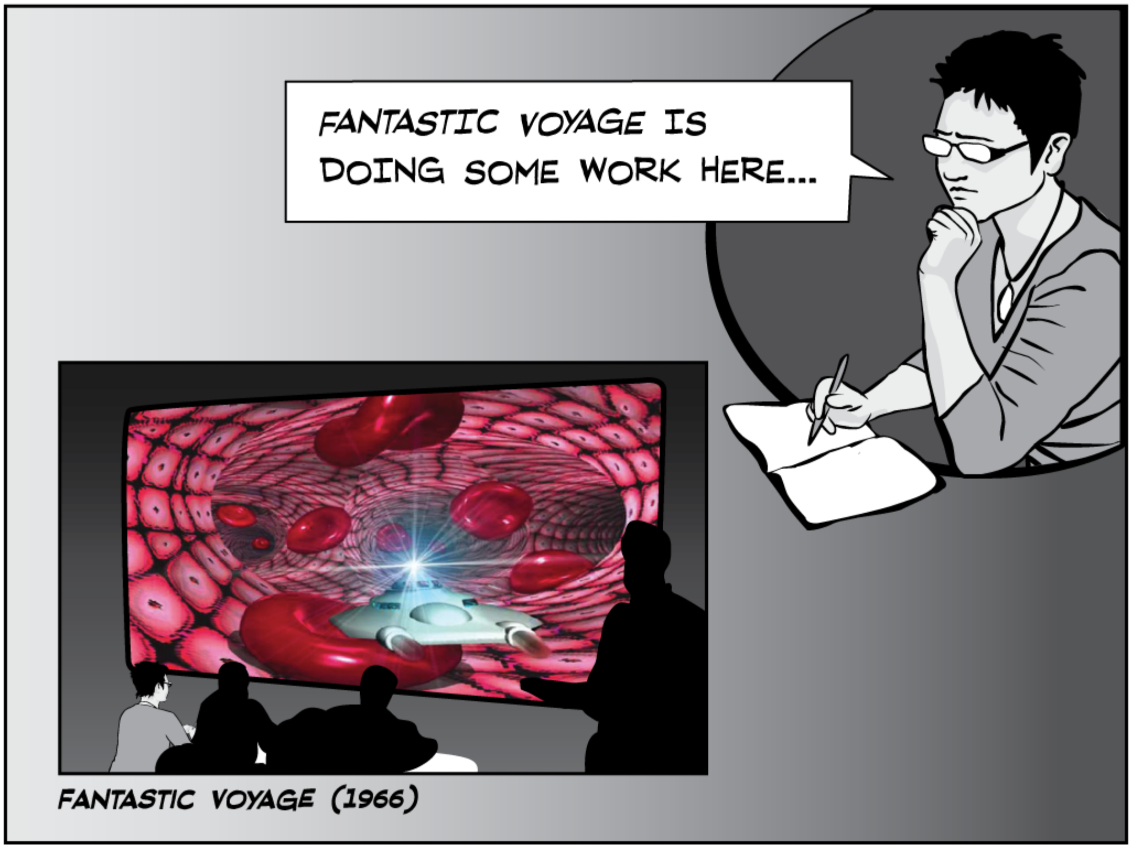

Illustration 43 *Fantastic Voyage* is doing some work.

But in order to demonstrate how the nano dream works as an apparatus of disciplinary production, it is necessary to show how it is a boundary-drawing practice. So far, in showing how it is invoked in the department, I've highlighted how particular aspects of the film are included in constructing the nano dream. That is, the film-cum-dream is fantastic, technophilic, beneficial, apolitical, and realizable. It represents progress through human ingenuity, it entails control of the material world, and it alternatively creates and collapses past, present, and future. Its portrayal of the inseparability of the human and technological is made irrelevant through humor, pejoratives ("simple-minded" and "trivial"), and exclusions. From analyzing what is included in the department's framing of the film, the ideals of nanoengineering and the nanoengineer begin to emerge: nanoengineering is a fantastic and visionary field that aims to control the material world on the small scale, and the nanoengineer is a scientist laboring to materialize her dreams of progress for the benefit of humanity.

Yet the nano dream emerges not only from what is included in this narrative of disciplinary history, but also from what is excluded. Taking the department at its word that *Fantastic Voyage* is a significant element of its disciplinary and departmental history, I do a short but close reading of the film to examine how exclusions are constitutive of a nanoengineering identity. Additionally, I show how these exclusions can be potential starting points for interventions.

Constitutive Exclusions

"Combined Miniature Deterrent Forces" : Constituting the nano dream through exclusion of the military narrative

The department frames the film as a medical narrative, constituting the nano dream as unproblematically good by including a story about saving lives and excluding the film's plot of developing a new military weapons technology. From the first moments of the film, it is clear that this is a story about a military mission. Benes, a Soviet diplomat, arrives in the United States at night on a tarmac amidst a heavy military presence, which establishes that this is no ordinary scientific visit or diplomatic mission. En route from the tarmac in a caravan of military vehicles, he is the target of an assassination attempt that leaves him in critical condition, unconscious with a blood clot.

In the next scene, Grant, a "Communications Expert" and ex-Frogman who is brought in to head up security (played by Stephen Boyd), is picked up in the middle of the night and taken to a massive underground military facility called the Combined Miniature Deterrent Forces, or the CMDF. The facility contains large gray corridors, is liberally adorned with CMDF insignia, and is bustling with uniformed men and women.

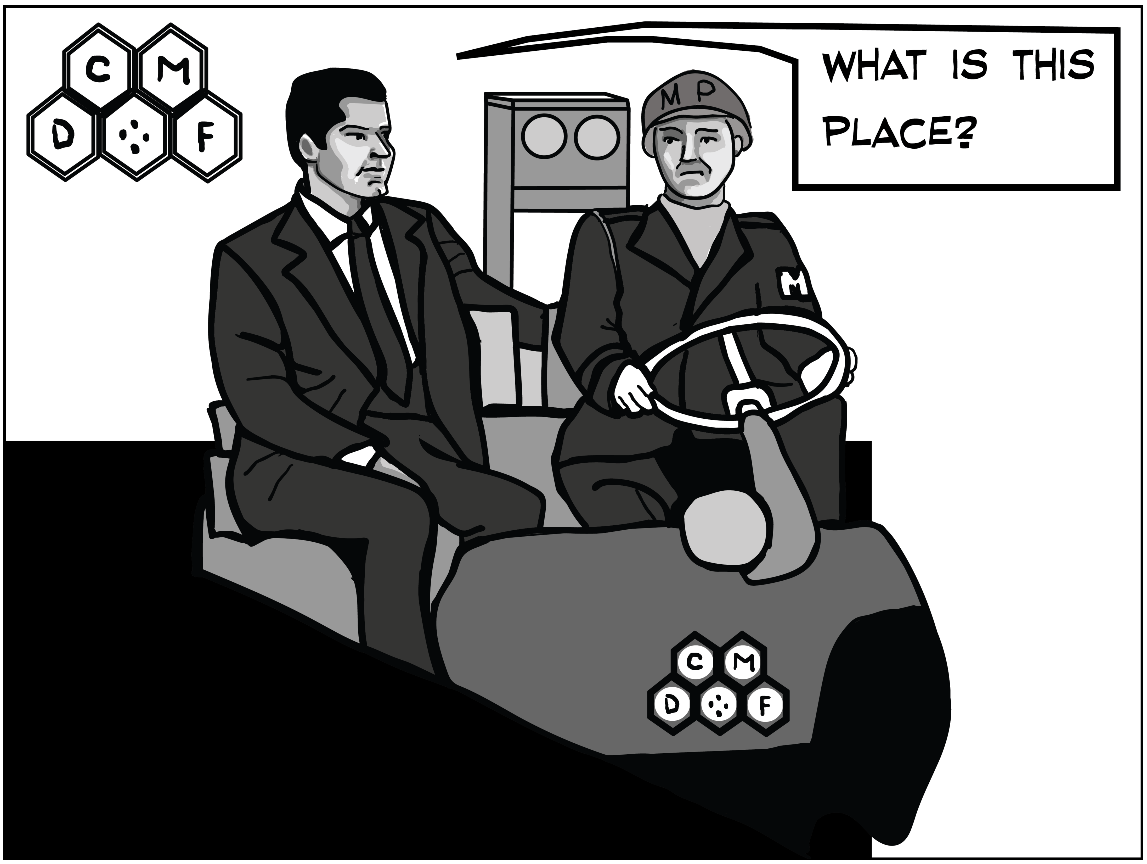

Illustration 44 *Fantastic Voyage* CMDF. Grant is taken to the top secret Combined Miniature Deterrent Forces facility.

Grant is taken via golf cart directly to General Carter, who then takes him to the Observation Room. They look down upon Benes, who is laying on an operating table.

"What the devil happened?" Grant asks.

"The Other Side got to him."

“How bad off is he?”

“Brain injury.”

“Before or after what he wanted to tell you?”

“Before he could breathe a word,” Carter says. “He’s the only scientist who knows the answer to what we’re after. That’s why we have to operate.”

Several things are established here: First, this is a story of the Cold War, and therefore it is a story of “our side” and the “other side.” Second, Benes is a Soviet scientist who intended to defect, to tell “our side” something important that only he knows. Third, the fact that he has suffered an injury *before* disclosing this knowledge is “why we have to operate.” They *will* operate to save his life, but the reason to do so is because they want his knowledge. The CMDF is presumably top secret; Grant, though a military man, has never heard of it, and he arrives at the facility only after the car transporting him is left on a platform that descends into the earth, a secret elevator to this underground facility. When he asks Carter what this place is, Carter answers: “We can shrink an Army—with all its equipment—and put it in a bottle cap. That’s why we call it Combined Miniature Deterrent Forces.” The name of this facility conjoins miniaturization with militarization.

Grant makes a silent whistle:

Illustration 45 *Fantastic Voyage*. Grant: "If the other side ever gets hold of that…"

Carter replies: "They have… But we've both got the same problem—lack of control. We can only keep things miniaturized for exactly sixty minutes. After that, everything starts growing back to its original size."

"I assume Benes knows how to control it."

"That's right. He wanted us to have the secret, and not them. Which is why they tried to kill him."

The "other side" tried to kill him, and "our side" is trying to save him for one reason: "Benes knows how to control it." A lack of control is the central problem, and absolute control over the miniaturization of matter constitutes the most valuable knowledge. This reveals another important way in which this film resonates with nanoengineers. It is not merely that a small submarine navigating the bloodstream to save a man's life bears resemblance to nanobot drug carriers that might eventually eradicate tumor cells. It is also about the ideal of being able to control matter at ever smaller scales. Recall that this was one aspect of Feynman's speech highlighted in the curriculum, and that the Foresight Institute claims that fourth generation nanotechnologies will arrive when we have achieved complete and absolute control over matter at the atomic scale. While many nanoengineers may not ascribe to the Foresight Institute's views about what constitutes control, the visual and verbal invocations of control throughout the curriculum and department do not generally unpack this term to indicate that it should be understood in a more limited way. The department's mission states that "Nanoengineering concerns itself with controlling matter on the molecular scale and manipulating processes that occur on the scale of nanometers."[32] This overarching theme of control melds with discussions of precision engineering, shaping molecules, and designing materials, and is articulated with invocations of Feynman's talk and images like the IBM logo made of 35 xenon atoms that physicist Don Eigler famously created in 1989 using a scanning tunneling microscope.[33]

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32. Mission statement of the department.

33. This act of using the scanning tunneling microscope to create the IBM logo from atoms, which occurred in 1989, is an iconic act of material control that simultaneously enacted corporate power. See IBM image here: http://researcher.watson.ibm.com/researcher/view_group_subpage.php?id=4251.

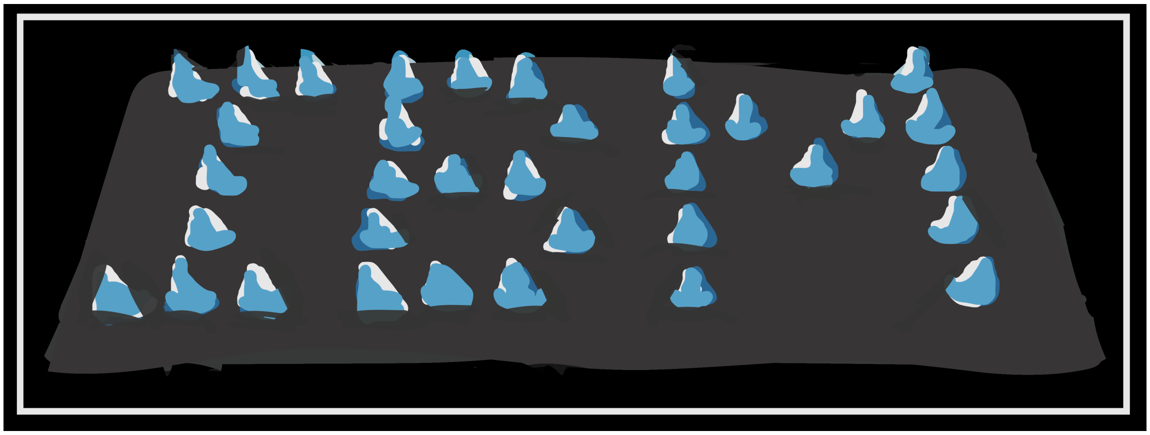

Illustration 46 IBM atomic scale logo. In 1989, Don Eigler used a scanning tunneling microscope to arrange individual atoms.

Together, the discourses of control in the department fit in with the themes of control in *Fantastic Voyage*, suggesting that control does indeed refer to precise manipulations of matter at ever smaller scales.

In the film, obtaining control over the material world is worth risking the lives of the crew in the submarine who have been shrunken down and injected into Benes' body. Dr. Michaels, the Chief of the Medical Section and one of the crew members, protests, "With all the unknown factors in the body, I still say risking five lives for one is something we should reconsider." Yet the medical doctor has mistaken the issue, framing it as a question of what should or should not be risked to save a man's life. As I've emphasized, saving a man's life is also how the nanoengineering department frames the mission in the film. But in the story, Dr. Michaels' concern is brushed aside. General Carter interrupts him: "We understand your concern, but we've made our decision, Doctor." This exchange between doctor and general highlights that the decision is expressly made by military command, not by medical experts; the purpose is to obtain Benes' knowledge for military ends. Reinforcing that this is a military mission, Grant says rhetorically, "How much can a man give to his country?" This phrasing reminds the viewer that the potential sacrifice of the crew is not for the sake of a human life, but for the state. They are potentially giving up their own lives for the military interests of the United States.[34] The fact that this is a military mission is also emphasized visually.

Illustration 47 The primary goal in *Fantastic Voyage* is to shrink an army to the size of a bottle cap and control its resumption to normal size.

34. In the context of the Cold War, it could be argued that risking the lives of the five crew members to obtain this knowledge is a morally robust wager in that obtaining military superiority could ultimately save lives. Yet this perspective is not developed in the department – which doesn't acknowledge this aspect of the film at all – or in the film. In the film, the issue is framed in terms of 'our side' and the 'other side', and there is no speculation about goals beyond an indication that both sides know how to shrink an army but neither, yet, know how to control miniaturization. That is, they do not have the capability to control how and when to return the army to its human scale. The race to be the first to obtain this military capability is, therefore, reminiscent of the nuclear arms race which is, at the least, morally questionable.

From the first moments of the film with the heavy military presence; to the imagery inside the CMDF, with CMDF insignia on all the walls, uniforms, and equipment; to the gridding and mapping of Benes' body as if it is a warzone, and the use of a "submarine" to enter his body, the film visually emphasizes that this is a story about a novel kind of military mission.[35] The mission to save Benes' life *is* a mission to acquire the knowledge to control miniaturization for military purposes. That is, the mission to save a life on the human scale is a mission to wage war better on a global geopolitical scale. And, on a microscale, saving a life is potentially achieved through waging war at the cellular level; the crew are operating within an antagonistic environment where they intend to destroy the blood clot through use of a powerful laser that visually resembles a large machine gun.[36]

Indeed, through the laser the film seems to reflect on the ways that some technologies can be used for good or ill—they are not inherently good. For example, when Grant first sees the laser, the technical assistant Cora (played by Raquel Welch) is in the process of testing it. It burns a hole into a piece of metal. Grant comments that such an instrument could be used to kill rather than to cure. Cora replies that this is not true so

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35. Nerlich, "Powered by Imagination," shows that the image of the nanosubmarine can be traced back to 1869 novel *20,000 Leagues Under the Sea* by Jules Verne, and that the same man who made the Nautilus for the Disney version of that novel made the Proteus for *Fantastic Voyage.* She interestingly points out that the nautilus "...also came to stand iconically for the 'progress of science', where the image of science as a voyage or journey is mapped onto 19th-century hopes invested in the positive outcomes of that journey, hopes which are still being conjured up by many biotech or nanotech entrepreneurs" (11).

36. Bernadette Bensaude-Vincent and Sacha Loeve, "Metaphors in Nanomedicine: the Case of Targeted Drug Delivery," *NanoEthics*, 8,1, 2014, 1-17. Bensaude-Vincent and Loeve argue that the 'therapeutic missile' metaphor in nanomedicine, used to frame nanobot drug delivery in terms of ballistics, is neither necessary or useful. They suggest that an 'oikological' approach, as one that emphasizes relationality, would get more at the affordances of both the nanoparticle and the biological milieu. In this site, one can see how the therapeutic missile metaphor gets reproduced within an epistemic community, and how popular culture – in this case, *Fantastic Voyage* – plays a key role in making the metaphor available.

long as it is in the hands of Dr. Duval, the lead neurosurgeon. But later, in fact, this laser is used to destroy the submarine—with the traitorous Dr. Michaels inside—while it is still in Benes' body. This ambiguity recalls to mind the verbal slip-up uttered by one of the professors when he said the crew entered the body to "kill" a hemorrhage, and then corrected himself to say that they were intending rather to "heal" the hemorrhage. And while the film may suggest that the technologies are neutral, their goodness or evil only determined by how they are employed by humans, it also troubles a notion of neutrality by portraying the entire technological assemblage as containing multiple politics and varying moral valences represented by the different crew members.

By including a narrative about a team of scientists saving the life of an important scientist and excluding the narrative of the military mission, the professors implicitly draw a boundary around what constitutes the nano dream and what is external, between what counts as relevant and what is just Hollywood. I have no reason to assume that this is an intentional goal or a planned exclusion; rather, from the perspective of a nanoengineer the plot elements of the 1966 film may seem self-evidently irrelevant. Yet the nano dream, and through it nanoengineering and the nanoengineer, are in any case produced through both what is included and excluded, so that it is here rendered ethical, universal and apolitical, belonging neither to "this side" or "that side," healing but not killing.

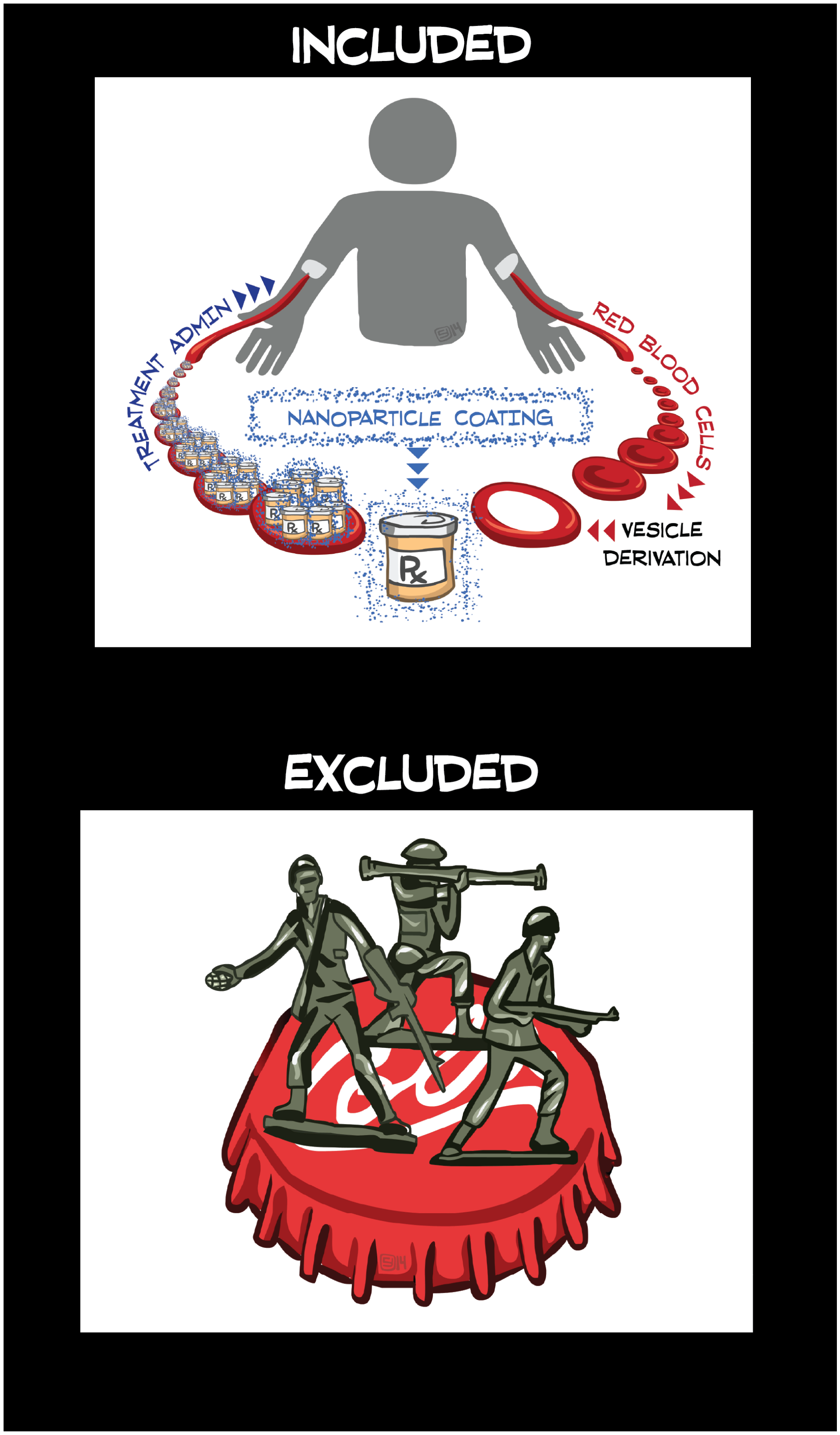

Illustration 49 Inclusion and exclusions are both important in constituting a nanoengineering.

While I am not aware of any weapons-related nanoengineering work occurring in the department, the Office of Naval Research and DARPA fund many of the on-going projects. But even the military-enabled projects are understood as producing benefit or potentially saving lives. For example, optical biosensors and drug delivery mechanisms can potentially be worked into military apparel to monitor the health of a service member and administer life-saving medicines. Other kinds of nano-enabled sensors could better detect IEDs or the presence of chemical weapons. These kinds of projects highlight that the ethics of engaging with the military are not easily delineated, and there are many who would not see the exclusion of this military narrative as a matter of depoliticizing or ethicizing nanoengineering. For example, one nanoengineering student who frequently demonstrates thoughtful engagement with questions of ethics and responsibility in interviews attributes her ethical code to her military training. When asked about potentially developing weapons following graduation, she indicated that she hopes that any weapons she creates would never have to be used, but that her ethics—grounded in a responsibility to defend—support her work on both defensive/protective and "aggressive" tools.[37] Still, by excluding the military narrative, at best the moral and ethical questions raised by military weaponry, war, and the militarization of scientific research are sidelined as irrelevant to the unproblematic good that nanoengineering is pursuing. This exclusion produces a goal- and object- oriented dream-to-reality materialization of nanotechnologies that is unfettered by complication or controversy, modeling an uncritical engineering ethos that refrains from engaging the messiness of technoscientific

37. NanoEngineering student, interview on April 7, 2014, transcribed by author.

production. While STS scholars and others have long said that technologies are not inevitabilities, that we must open up these black boxes to reveal the messy contingencies that lead to their particular materializations,[38] this exclusion of the military narrative models the nano dream as already blackboxed; the end is the beginning.

The "Control Room" : Constituting nano's promise of material control by excluding the failures, risks, and uncertainties attending its pursuit

By emphasizing the ways that the "dream" of *Fantastic Voyage* is being realized in the department now, and excluding the film's portrayal of multiple failures, risks, and uncertainties in pursuing control, the faculty implicitly reinforce the promise of succeeding at total material control. Control of the material world is a major theme in both the film and the emerging field of nanoengineering. The military mission to save Benes' life in order to gain his knowledge of control is an aspirational goal. And the presumption of control is manifest from the beginning through the metaphor of controls—mechanical dials, switches, buttons—and through the sterile empty Observation Room where Benes' body lays inert. But the lack of control prevails in the action of the story in the form of human and technological breakdown in the face of material agency.

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38. Bruno Latour, *Pandora's Hope : Essays on the Reality of Science Studies*. Cambridge, Mass.: Harvard University Press, 1999; Trevor Pinch and Wiebe Bijker, "The Social Construction of Facts and Artifacts: Or How the Sociology of Science and the Sociology of Technology Might Benefit Each Other," In *The Social Construction of Technological Systems New Directions in the Sociology and History of Technology*, edited by Wiebe E. Bijker, Thomas Parke Hughes, T. J. Pinch and Deborah G. Douglas, Cambridge, Mass.: MIT Press, 2012, 11-44; Langdon Winner, "Upon Opening the Black Box and Finding It Empty: Social Constructivism and the Philosophy of Technology," *Science, Technology & Human Values* 18, no. 3 (1993): 362-78. See Latour for a definition of blackboxing. See Pinch and Bijker for the argument to open up the black box. And see Winner for a critique of STS analyses that "open the black box" but that are not grounded in an ethical, critical stance.

Illustration 50 The control room in *Fantastic Voyage*.

For example, in the "Control room" which overlooks the operating theater where Benes lays unconscious and which represents the "objective view" according to the screenplay, various technicians flip switches and move dials. Large anatomical images and x-rays of the heart are displayed, along with an equally large EKG chart that shows the electronic representation of Benes' beating heart. According to the screenplay, the chart "is in constant operation via remote control."[39] The miniaturization platform, "Zero Module" is operated by the "Miniaturization Control Panel." Inside the submarine, the captain

39. Harry Kleiner, "Fantastic Voyage," December 22, 1964 revised February 26, 2/26/1965: Scene 82.

indicates to Grant that the "controls are highly sophisticated. There's a button for everything." However, once miniaturization occurs, the various buttons do not in fact allow the crew to control the situation. Control is merely an illusion.

First, we see a failure of human self-control. Dr. Michaels has a traumatic flashback to wartime experience, panics as the submarine is submerged into water, and nearly opens the hatch to escape. His panic is described in the screenplay as "irrational terror."[40] Fellow crew members manage to restrain and talk him down, but it is the first indication that control is illusory. Second, we see the unpredictability of the environment –in this case, a human body—when the sub is unexpectedly swept into a current of blood and thrown off course. Then there is a failure of technology. The Captain fiddles at his controls, and cries out: "She won't respond!" Strong vibrations buffet the passengers. The sub enters a massive whirlpool, and the centrifugal force whips Grant and Cora to the sides of the submarine. The sub gets sucked through the whirlpool and through a fissure, which leaves them farther off course. Going forward would entail going through the heart, which could kill them and doom the patient, but they are not able to go back the way they came. General Carter, unwilling to call off the mission, proposes that they stop the heart for sixty seconds, theoretically not so long that they can't revive Benes, but just long enough for the sub to pass through the heart unharmed. Although they do get through the heart, the challenges keep coming. The submarine loses air pressure, necessitating that Grant put on his snorkel suit and exit the sub in an effort to get air from Benes' lungs into the submarine. Then Grant is nearly lost inside the lungs when he faces

40. Kleiner, *Fantastic Voyage*, Scene A-154.

hurricane-like winds. Additionally, when they pass through the inner ear canal and a nurse outside the body in the operating room drops a scissors, the vibrations fling them around, and Cora nearly dies. Finally, Dr. Michaels turns out to be a double agent working for the "other side." He destroys the laser that was intended to clear the brain clot and attempts to take over the ship. The others barely escape the immune system's attack as they swim to escape Benes' body through his tear duct. The film ends upon their escape from the body, never actually addressing whether they managed to clear the brain clot, save Benes' life, or obtain the knowledge he had. Though the Control Room suggests that this operation will be completely controlled, in fact a failure of control manifests throughout the entire non/human mission. The failures stem from psychological, technological, environmental, social, and political sources.

"Our Side" and "The Other Side": Constituting boundaries by excluding the multiple human and nonhuman figures and the multiple politics at work

When the department frames the film as a medical narrative including only scientists, and demarcates the submarine (the "microtechnology") from the humans inside it ("Hollywood"), it excludes the film's portrayal of technology as a complex human-nonhuman material-discursive artifact containing multiple politics. Recall that five human beings enter a nuclear-powered submarine, the submarine is then shrunk down and placed into a hypodermic needle along with saline, and this solution is inserted into the bloodstream of a human body. The technology deployed in this military mission consists of the military chief medical officer, the ex-frogman security personnel, the naval captain, the neurosurgeon and his female assistant, the snorkel suits they wear, the wireless communications system they use, the laser, and the nuclear powered submarine.

The nanoengineering department frames this assemblage as the “nanotechnology” of this mission. As such, the miniaturized submarine visibly contains within it human and nonhuman elements, and makes ambiguous this distinction. As a human-nonhuman hybrid, as a material-discursive object and practice, as a thing that is at once inside and outside, this little submarine’s “fantastic voyage” disrupts a classical realist view of technology as inert and apolitical materiality. There are moments when the film’s screenplay alludes to a self-awareness of the messiness it has introduced in this regard. For example, when the submarine and crew are initially shrunk but not yet inserted into the hypodermic needle, people come to inspect the shrunken sub from the outside. The people look enormous from the perspective of the crew. The screenplay reads: “Grant and the others react to the first sight of the oncoming human beings in relation to their own reduced size: a button is immense, a shoe—although far down from their position on the Zero Module—is long as a city street, the heads gargantuan atop skyscraper-tall bodies.”[41] Up until now, the screenplay has referenced male and female officers, generals, colonels, technicians, and specialists, but in this moment the crew sees “human beings,” as if to suggest that their own status as “human being” has been destabilized.

The entangled human-submarine entity in the film enacts agency and it is political in myriad ways. Its mission subordinates medical goals to military goals. It operates on behalf of “our side” in the war against the “other side.” As a non/human and material-discursive entity, this submarine contains “irrational terror” and a hierarchy of authority, ambivalence about the relationship between God and science (there are tense exchanges

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41. Kleiner, *Fantastic Voyage*, Scene 135.

between the surgeon and the doctor about the small "universe" they are witnessing), gender politics (in the relations between Cora and the rest of the crew), and controls that fail to control. It also manifests the "other side" in the traitorous actions of Dr. Michaels within the "our side" of the rest of the crew, ever disrupting the easy dichotomization of *this* and *that*, *us* and *them.*

The film also confounds easy narratives of scale. The film begins with: "Man is the center of the universe. We stand in the middle of infinity between outer and inner space, and there's no limit to either."[42] But a closer analysis suggests that scale is itself produced through the material and discursive practices of knowing the material world. It is not merely a property of a static spatial container within which the body is situated.[43] The film certainly portrays miniaturization and is invoked for its portrayal of miniaturization. Yet it shows scale not as static and singular but as dynamic and multiple. Saving Benes' life entails making humans in a submarine small and making Benes' body a universe. Man is figured not just as the center between micro and macro, or between inner and outer space, but as variably scaled: as microscale, figured by the team that is miniaturized inside Benes' body; as human scale in the body of Benes in the operating room of the CMDF; and as macroscale in the body of Benes as experienced by the team that is miniaturized inside his body. And these scales are not static, but are changing as the team shrinks and expands. In this sense, I do not think it is only working to privilege

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42. Richard Fleischer, "Fantastic Voyage," 100 minutes, 20th Century Fox, 2007/1966.

43. Barad, *Meeting the Universe Halfway*.

the human scale by collapsing scale.[44] It may be visually privileging the human scale, but at the same time it is showing scale to be perspectival, dynamic, and emergent. Moreover, the act of clearing a clot in Benes' brain itself produces local, national, and global scales. That is, as an act in the body of a man in an operating room at the CMDF, it produces the local; as an act of obtaining knowledge within a military mission to produce new weapons of war, it produces the national; as an act performed on a Soviet scientist by a U.S. military team in order to shrink an army to position it behind Soviet lines as part of the Cold War, it produces the global. By excluding the messiness of what constitutes human and non human, micro scale and macro scale, inside and outside, our side and the other side, the department's framing of the film highlights what is relevant and irrelevant for nanoengineering and the nano dream. And what is relevant is a somewhat simple delineation of technology that is apolitical.

"Zero Module": Constituting universality by excluding questions of race, gender, and social location

What is included in the faculty's narrative of the film is a story that has no location, no time or place or other indication that the fantastic voyage is one that is white, male, western, and located within a Cold War moment. The inclusion of a generic story

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44. Horton, "Collapsing Scale." Horton argues that 'scalar collapse' - "a process by which objects occupying two or more different scales are articulated together and made commensurate so that the difference between them is elided" - privileges the scale of the human individual while "eliding significant differences of scale and complexity" (1). I agree that 'scalar collapse' is happening in the film, particularly when still images of the film are analyzed. Such collapse is also produced in the ways that scale is introduced to students in this department. However, when viewing the film in movement and taking into account the story, I think it is also showing a more fluid kind of movement between and through scales, such that even though the viewer sees a human scale – and in this sense the human scale is privileged - the humans in the film are not themselves human scale. In this sense, scale is not static, and the human is not easily situated between macro and micro scales.

of scientists constitutes the nano dream as universal even as the exclusion of the specific story reproduces the boundary that—however unintentionally — preserves the nano dream as a white, masculinist, western, military-industrial dream. The characters in the film are all white, and traditional gender views are on display from the first moments of the film. In fact the trailer for the film sets the tone when it claims that "Four men and a beautiful girl [are] off on a fantastic voyage," signaling that the woman in the story—a "beautiful girl"—does not have the same status as the men. When the military car first picks Grant up to take him to the CMDF, Grant appears to be getting into his clothes still and indicates that he thought he was on vacation. He has a smudge of lipstick on his cheek. Another man in the car wipes with the smudge off with a handkerchief and throws the handkerchief out the window. The first shot of Grant establishes his virility, with the lipstick indexing woman, sex, and the inconsequence of the feminine that he leaves behind as he transitions back into the man's world of his profession. He is taken *from* the lipstick place *to* the gray, sterile, bustling military environment of the CMDF, where he will become part of this important military mission. Upon arrival, as he is shuttled around in a cart, he pays special attention to the female personnel, whose uniforms indicate they are not military. Through his gaze and their attire, the presence of women in the CMDF is reaffirmed as auxiliary; they are there to serve the men. Though there is one women who is a part of the crew, this is explicitly controversial.

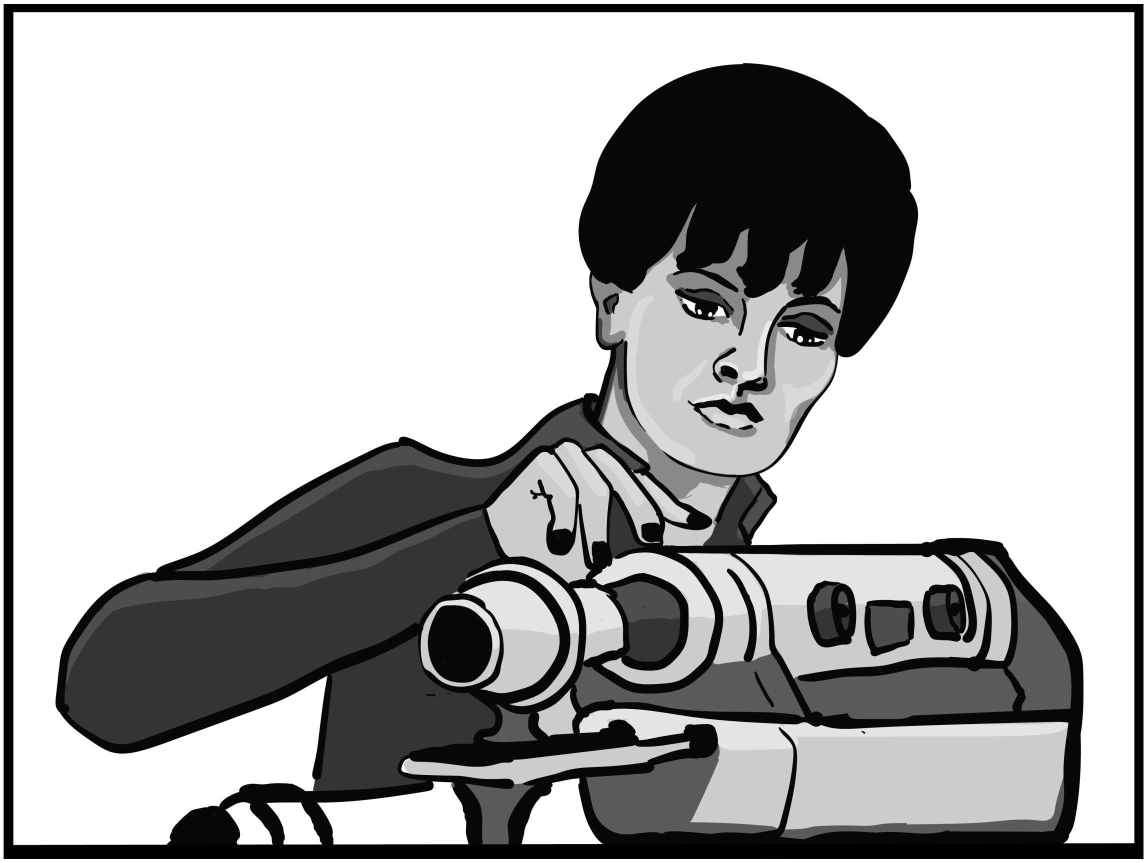

Illustration 51 Cora, played by Raquel Welch. The film engages gender politics to some extent. On the one hand, she is sexualized and referred to as a "beautiful girl." On the other, there is an explicit discussion about her role in the mission, and Dr. Duval insists that she come because her skills are top-notch.

When Grant asks the general about Cora, Dr. Duval's technician, he asks if she is okay "in addition to the looks department." The General replies that she is loyal. Later, there is a fierce disagreement among the crew about whether she may actually join. Duval gets his way, but not before others go on record voicing that this is no place for a woman and that they do not want her there. Once the voyage is underway, Cora becomes the object of Grant's protection. In one titillating scene, she is stretched out against the sinews of bloody tissue near the lungs as she is buffeted by gales of wind. Wearing a tight white body suit, her arms are pinned behind her, her legs are splayed apart, and she heaves her breasts in distress as Grant works to rescue her.

Cora is a technician and her presence is deemed essential, yet she is marginalized and threatened by her colleagues and the environment, and here she is repeatedly made into an object. The “zero” of “Zero Module” connotes nothing and nowhere. And it suggests a kind of beginning, the ur-moment of a linear timeline of progress: next is one. But Zero Module is not nowhere; it is somewhere very specific. Namely, it is in a masculinized, technicized, militarized, Cold War environment of the 1960s in the United States.

Conclusion

I have claimed that framing *Fantastic Voyage* as a vision of nanotechnology that is currently being realized in the department inscribes the past and future into the present, and produces the nano dream as a boundary-drawing practice that circumscribes nanoengineering as intrinsically good. The nano dream is cast as universal and apolitical—it is about scientists benefitting society or humanity. This reflects language often used in the department, for example, in the mission statement, which says that nanoengineering creates devices “to be utilized by mankind.”[45] The medical vision of saving a human life exists within the dream, while the military vision of controlling miniaturization in the machinery of war is excluded. The nano dream promises inevitability and success in fully controlling the material world, while the multiplicity of

45. Department mission statement.

failure is excluded.

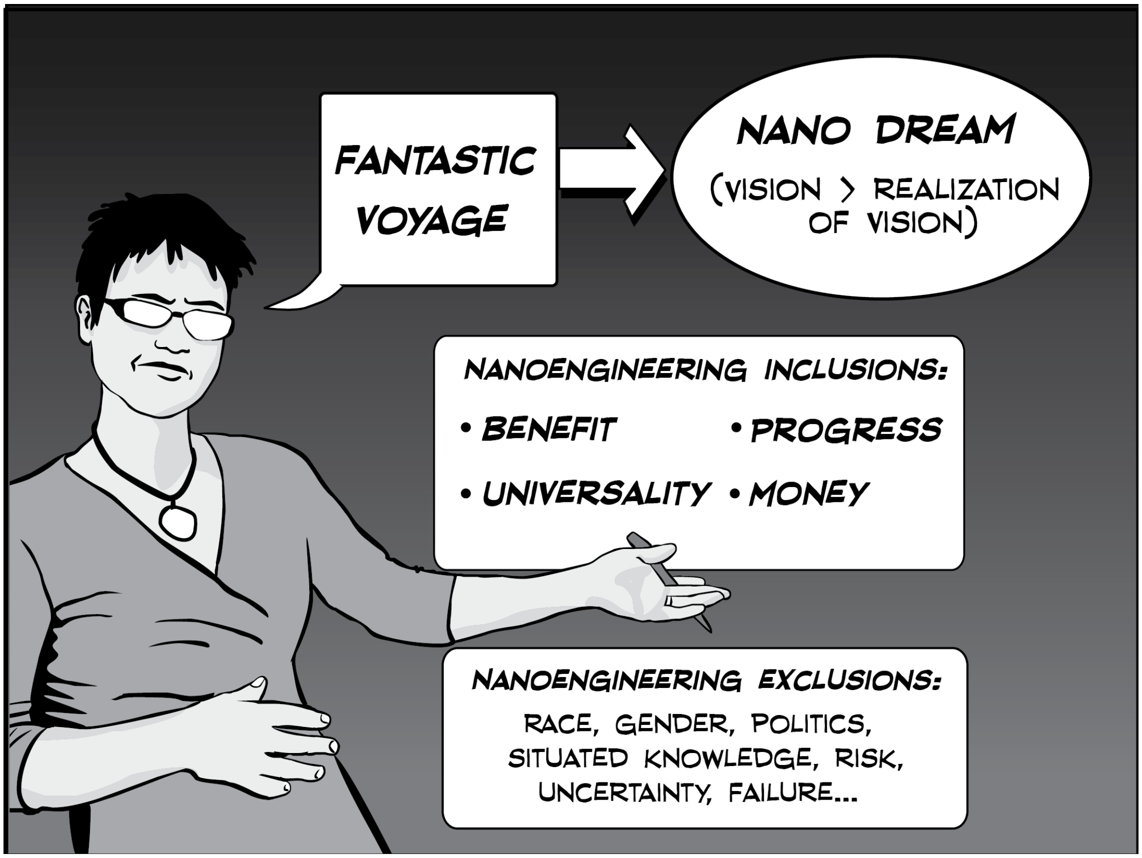

Illustration 52 Argument review.

Fantastic Voyage additionally provides a framework through which nano can be articulated to a very particular kind of outsider: the student who will become a member of the community by the time she graduates as a nanoengineer. It establishes the primary themes, the worldview, the temporal orientation, and the identity of this new category of scientist-engineer-entrepreneur, upon which additional stories, discussions, pictures, and activities can then elaborate.[46] Crucially, the way the film is used in the curriculum performs a cut between what counts as relevant and irrelevant that potentially de-

46. See Haraway, *Primate Visions*, for analysis of the intertextuality of such stories.

responsibilizes the nanoengineer. In the context of contemporary research efforts in the department, students learn specific futures—futures in which cancer will be cured, solar energy will be widespread, and batteries will be long-lived. However, through *Fantastic Voyage*, students learn that underlying these specific materializations is an open future,[47] one that is shaped according to their own visions as nanoengineers, and that follows the ethos of mimicking and dominating nature in the service of progress. Even though the film portrays a specific vision about medicine, the way the film is framed in the curriculum emphasizes that any nano dream can be realized, to inspire students to pursue their own nano dreams. Dreaming the future is an activity that is encouraged as part of their new identity. Making the future according to one's dreams is part of the power of the nanoengineer. Yet dreams can be framed differently. According to the professors of Intro I and Intro II, the dream of the film is one of a new field that uses miniaturized technologies to save a human life, a dream that aligns with the oft-repeated phrase of using nanotechnologies for the benefit of humanity.[48] As articulated through this film, the nano dream perpetuates a relationship to what is relevant and irrelevant that narrowly delimits the nanoengineer's responsibility.

But the film offers many possibilities for complicating this narrative in productive ways. What is obscured in the professors' account of miniaturization in the film is that

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47. Barbara Adam and Chris Groves, *Future Matters: Action, Knowledge, Ethics*, Supplements to the Study of Time, Leiden; Boston: Brill, 2007. I use the term "open future" as defined by Adam and Groves: "The contemporary future is no longer assumed to be predestined but subject to human shaping and transformation" (199).

48. This language is also used by the National Nanotechnology Initiative: "…Applications of nanotechnology are delivering in both expected and unexpected ways on nanotechnology's promise to benefit society." http://www.nano.gov/you/nanotechnology-benefits.

the technological and the human are mutually entangled, the human and nonhuman elements that constitute the technology contain multiple politics, the uses of this miniaturization are multiple (from saving lives to creating novel new weapons), the precision and control promised by the technology are never fully realized, and there are multiple instances of social, political, environmental, and technological failure. The film displays the race, gender, and other social and cultural values and biases of its day, and disrupts classical notions of man, nature, and scale. The constitutive exclusions I outlined could be starting points for inviting students into a critical and reflexive conversation about the societal dimensions of nanoengineering. The film provides plenty of room to consider broad questions: What constitutes technology? What is meant by "control" and what are the implications of achieving it? What is left out of a nano dream, who may or may not benefit from any particular dream, and for whom might a nano dream be a nano nightmare? How can nanoengineering as a discipline strive to be inclusive with respect to race and gender? Such engagement models responsibility as an ongoing process of interrogating one's nano dream and one's nanotechnology research and development.

Nanoengineers are not trained to do a close reading of a film in the same way as is a person trained in the humanities or social sciences. From the perspective of an engineer, these details about the film may seem irrelevant—they are the story part, the Hollywood part, extraneous to the vision of nanomedicine that they see in this film. Yet it is this boundary drawn between what counts as relevant and what is deemed irrelevant that I am challenging. It is this separation between scientific practice and a reflexive engagement with scientific practice, and between nature and culture, that is inadequate to prepare scientists and engineers to intra-act responsibly with the world.

Chapter 2 extends and elaborates on material that appears in "Nanodreams and Nanoworlds: Fantastic Voyage as a Fantastic Origin Story," *Configurations*, Fall 2015, Volume 23, Number 3, pp. 263-299. The dissertation author was the primary investigator and author of this paper.

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Chapter 3 Smaller is Better? Learning an Ethos and Worldview in Technical Education

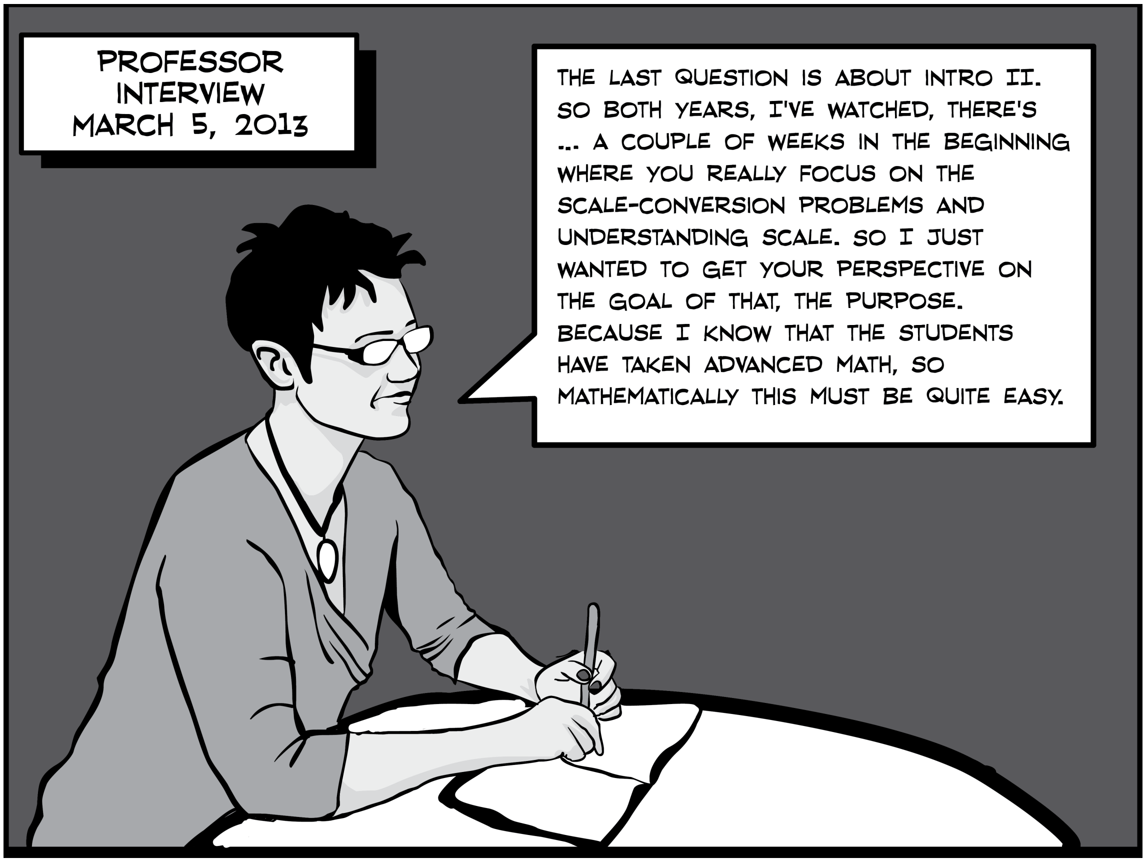

Illustration 53 I ask a NanoEngineering professor about his goals in the scaling laws lectures.

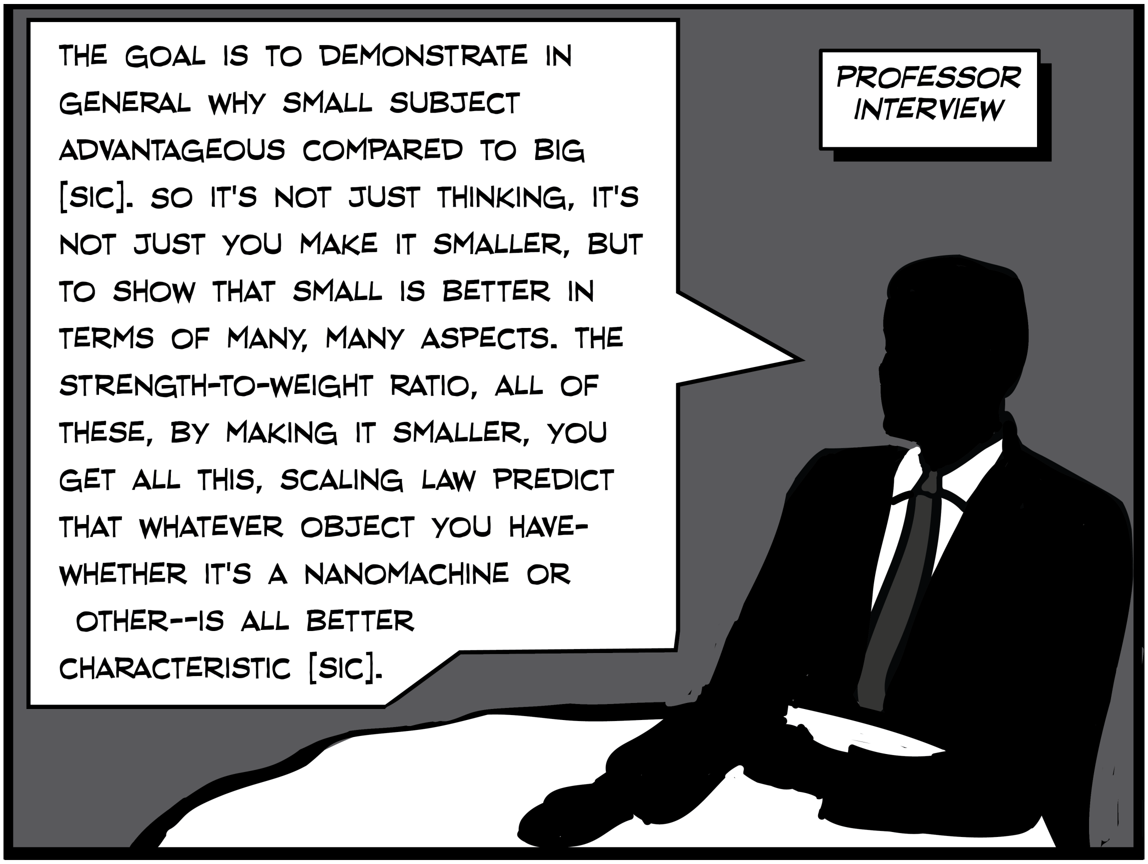

Illustration 54 The NanoEngineering professor says, "The goal is to demonstrate in general why small subject advantageous compared to big [sic]. So it's not just thinking, it's not just you make it smaller, but to show that smaller is better in terms of many, many aspects. The strength-to-weight ratio, all of these, by making it smaller, you get all this, scaling law predict that whatever object you have—whether it's a nanomachine or other—is all better characteristic [sic]."[1]

Introduction

In Chapter 2, my focus on *Fantastic Voyage* was an examination of the ways a cultural object is taken up within the curriculum and broader disciplinary formation of a scientific community. I presented this Hollywood science fiction film as a self-evident cultural object, an outsider's cultural representation adopted by a scientific community. In so doing, I may have implicitly suggested—against my own intellectual

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1. Interview with NanoEngineering professor, May 5, 2013, transcribed by author.

commitments—that there is a natural distinction between the cultural object of the film and the technical objects of the other curricular and disciplinary practices of the community. In this chapter, therefore, I want to examine another set of lectures and practices in the classroom that do not coalesce around a specific object, such as a film, but that are organized as part of a specific unit in the curriculum. This unit introduces students to scale and to a set of mathematical expressions that describe the physical consequences of changes in scale, referred to as the "scaling laws." I will show that the collection of lectures, images, homework assignments, and other activities that are part of this unit constitutes cultural work that exceeds the technical goals of the unit and indeed challenges the idea that there is a natural distinction between the cultural and the technical objects of a scientific community. While this claim at face value is not new within the field of science studies, my work focuses on the higher-ed science classroom rather than the laboratory. The higher-ed science class is a key site for understanding how the ethics and politics of knowledge production are articulated within disciplinary production and training, and how technical lectures are also cultural practices.

The assumption that smaller is better is key to nanotechnology's central promise—that manipulating matter on the nanoscale will enable novel applications in nearly every domain of contemporary life. This is not only the case in the NanoEngineering Department. The National Nanotechnology Initiative (NNI), for example, states that its vision "is a future in which the ability to understand and control matter at the nanoscale leads to a revolution in technology and industry that benefits society."[2] Its list of nanotechnology highlights reads like a poster for the underlying theme that smaller is better, with titles for stories such as "The Business Potential of (Amazing, Wonderful, Futuristic) Graphene" and "Can Solar Energy Get Bigger by Thinking Small?"[3] These phrases don't explicitly say that smaller is better, but they work from this premise. As I have suggested in Chapter 2, the department locates its origins in Richard Feynman's 1959 talk "There's Plenty of Room at the Bottom," and indeed Feynman's argument that there is "*plenty* of room at the bottom" which will yield an "enormous number of technological applications" and "economic applications"[4] previews the tight coupling of the technical and the economic in scaling down.[5] Often formulated in relation to what Colin Milburn refers to as the "'small wonders, endless frontiers' of nanodiscourse," this theme is therefore not surprising or new, and it appears in various guises in nanotechnology research articles, blog posts, and industry news.[6]

In any particular context, smaller may be deemed better by those producing or using a specific technology—either because an existing functionality can be made more cheaply and efficiently, or a new functionality is made possible. Yet in the abstract,

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2. National Nanotechnology Initiative, "Nanotechnology Facts."

3. National Nanotechnology Initiative, "Slideshow," accessed September 25, 2014, http://nano.gov/slideshow-archive.

4. Richard Feynman, "There's Plenty of Room at the Bottom," *Engineering and Science* 23, no. 5 (February 1960): 22.

5. Chris Toumey, "Reading Feynman Into Nanotechnology: A Text For a New Science," *Techne* 12, no. 3 (2008): 133-68; Andreas Junk and Falk Riess, "From an Idea to a Vision: There's Plenty of Room at the Bottom," *American Journal of Physics* 74, no. 9 (2006): 825-30; Colin Milburn, *Nanovision: Engineering the Future*, Durham: Duke University Press, 2008. See Toumey, Junk and Riess, and Milburn for discussions of how Feynman is made into the father figure of nanotechnology outside of this department.

6. Colin Milburn, *Nanovision*, 96.

incorporated into the very identity of nanoengineering, *smaller is better* becomes a universalizing logic that not only hitches the technical to the economic but also to the moral. That is, *smaller is better* travels alongside nano's promise to benefit society and works to unite the technical affordances of the nanoscale with the promissory visioning of social and economic benefit. While the nanoengineers I've asked acknowledge that there is always some risk with new technologies and that any given nanotechnology could potentially be used for ill, they often see their own projects as unproblematically and universally good. The market is widely seen as an adequate (and often ideal) mechanism for determining acceptable risk and for discouraging the development of technologies that are not sufficiently beneficial.[7] In this context, *smaller is better* as a matter of moral conviction—as well as a driver of research and innovation—eclipses the possibility that there may be contexts or perspectives from which smaller *is not* better that have not already been rooted out by the market.

The curricular unit on scale that I am examining in this chapter occurs in an introductory undergraduate nanoengineering course required of all second-year majors, which I observed two years in a row. Through this analysis, I show how *smaller is better* as a worldview gets tethered to what nanoengineers in my site would understand as technical knowledge central to their field. I blend feminist STS and communication studies to show how the cultural values of science and its practices are produced in the

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7. Langdon Winner, *The Whale and the Reactor: A Search for Limits in an Age of High Technology*, Chicago: University of Chicago Press, 1986. See Winner for a discussion of socially determined technological limits. [To do: define this and connect to main text]

classroom, not only in the laboratory,[8] and to examine the constitutive exclusions of nanoengineering[9] and its universalizing assumptions.[10] I additionally build on Charles Goodwin's articulation of "professional vision"[11] and Mikhail Bakhtin's notions of dialogism and heteroglossia[12] to show how the rhetoric of nanoengineering lecture courses contributes to a professional vision that sees smaller as better.

I argue that *smaller is better* must be understood as a central principle of the identity, practice, and disciplinarity of nanoengineering as crafted in this site. Each aspect of this curriculum—learning the scaling laws as technical know-how, learning an embodied and naturalized relation to the nanoscale and to scale traversal, and learning the

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8. Deborah Johnson and Jameson M. Wetmore, "Sts and Ethics: Implications for Engineering Ethics" in *The Handbook of Science and Technology Studies*, edited by Edward J. Hackett and Society for Social Studies of Science, (Cambridge, Mass.: MIT Press in cooperation with the Society for the Social Studies of Science, 2008), 567-81; Cyrus Mody and David Kaiser, "Scientific Training and the Creation of Scientific Knowledge" in *The Handbook of Science and Technology Studies*, edited by Edward J. Hackett and Society for Social Studies of Science, (Cambridge, Mass.: MIT Press in cooperation with the Society for the Social Studies of Science, 2008), 377-402. She Johnson and Wetmore, and Mody and Kaiser for discussions of STS's engagement with the higher-ed classroom.

9. Karen Barad, *Meeting the Universe Halfway: Quantum Physics and the Entanglement of Matter and Meaning*, Durham: Duke University Press, 2007.

10. Donna Haraway, *Primate Visions: Gender, Race, and Nature in the World of Modern Science*, New York: Routledge, 1989; Sandra, Harding, "Rethinking Standpoint Epistemology: What Is "Strong Objectivity"?" in *Feminist Epistemologies*, edited by Linda Alcoff and Elizabeth Potter, (New York: Routledge, 1993), 49-82; Jenny Reardon, "Decoding Race and Human Difference in a Genomic Age," *differences: A Journal of Feminist Cultural Studies* 15, no. 3 (2004): 38-65; Helen Longino, *Science as Social Knowledge: Values and Objectivity in Scientific Inquiry*, Princeton, N.J.: Princeton University Press, 1990. For discussion of universal assumptions in western scientific practice, see Haraway *Primate Visions*, Harding *Rethinking Standpoint Epistemology*, Reardon *Decoding Race*, as well as a theorization of feminist epistemology by Longino *Science as Social Knowledge*.

11. Charles Goodwin, "Professional Vision," *American Anthropologist* 96, no. 3 (1994): 606-33. Goodwin argues that through highlighting, pointing, and work-specific practices of making sense of graphical images, professions produce an apparatus of vision that allows them to see the objects of knowledge central to their profession.

12. Mikhail Bakhtin, *The Dialogic Imagination: Four Essays*, trans. Michael Holquist, Austin: University of Texas Press, 1981.

normative stance that *smaller is better*—helps to constitute a particular way of looking at the world. The Department of NanoEngineering understands itself as a logical and inevitable materialization of the 21st century, capitalizing on the confluence of natural age-old bottom-up nanotechnologies, the more recent development of new instrumentation that allows visualization and manipulation of nanoscale phenomena, the (triple helix) imperative to innovate,[13] and the (neoliberal) push to produce the intellectual and human capital of the future[14] with an emphasis on inter- and trans-disciplinary knowledge production.[15] Within this confluence, these lectures and problem sets constitute a sociotechnical apparatus that produces an ethos of *smaller is better*, while simultaneously circumscribing nanoengineering as a field invested in validating this moral and political claim. It is a moral claim because it presumes that nanoengineering's capacity to "go smaller" will ultimately create progressive benefits for humanity. And the desire to control and manipulate matter at any scale is inherently political, even and perhaps especially when the scale is invisibly small, at the level of individual atoms and molecules. That is because work on this scale requires particular tools, training, and

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13. Henry Etzkowitz, *The Triple Helix: University-Industry-Government Innovation in Action*, New York: Routledge, 2008.

14. Philip Mirowski, *Science-Mart : Privatizing American Science*, Cambridge, Mass.: Harvard University Press, 2011; Philip Mirowski and Esther-Mirjam Sent, "The Commercialization of Science and the Response of Sts," In *The Handbook of Science and Technology Studies*, edited by Edward J. Hackett and Society for Social Studies of Science, 473-98, Cambridge, Mass.: MIT Press ; Published in cooperation with the Society for the Social Studies of Science, 2008.

15. Michael Gibbons, Camille Limoges, Helga Nowotny, and Simon Schwartzman, *The New Production of Knowledge : The Dynamics of Science and Research in Contemporary Societies*, London ; Thousand Oaks, Calif.: SAGE Publications, 1994; Helga Nowotny, Peter Scott, and Michael Gibbons, *Re-Thinking Science : Knowledge and the Public in an Age of Uncertainty*, Cambridge Malden, MA: Polity ; Published in the USA by Blackwell, 2001.

funding to make matter visible and manipulable, rendering the nanoscale the domain of some, presumably on behalf of others.

As an ethos, it also concretizes disciplinary boundaries, excluding research programs that study ways in which *smaller is not better*. For example, the nanoengineering curriculum occasionally raises the subject of nanotoxicology, but presents it as a separate field, implicitly setting aside potentially toxic health or environmental effects as the concerns of a different discipline. While nanotoxicology may necessitate specialization and ultimately constitute a distinct field, by placing it outside the field of nanoengineering—and not offering it as a concentration or major to these students—these disciplinary boundaries affirm the identity of nanoengineering as one that is bound by the good.

Finally, s*maller is better* connotes a practice of world-making that, despite treating the nano world as a discrete space, conflates the in/visibility of the nano world with the in/visibility of the future.[16] That is, visualizing and materializing the nano world is simultaneously an act of visualizing and materializing the macroworld, in an ongoing effort to make an (un)anticipated future a present reality.[17]

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16. See Milburn *Nanovision* for a discussion of how "nanovision" brings the future into present reality.

17. Vinceanne Adams, Michelle Murphy, and Adele Clarke, "Anticipation: Technoscience, Life, Affect, Temporality," *Subjectivity* 28 (2009): 246-65. See Adams, Murphy, and Clarke for a discussion of anticipation in technoscience.

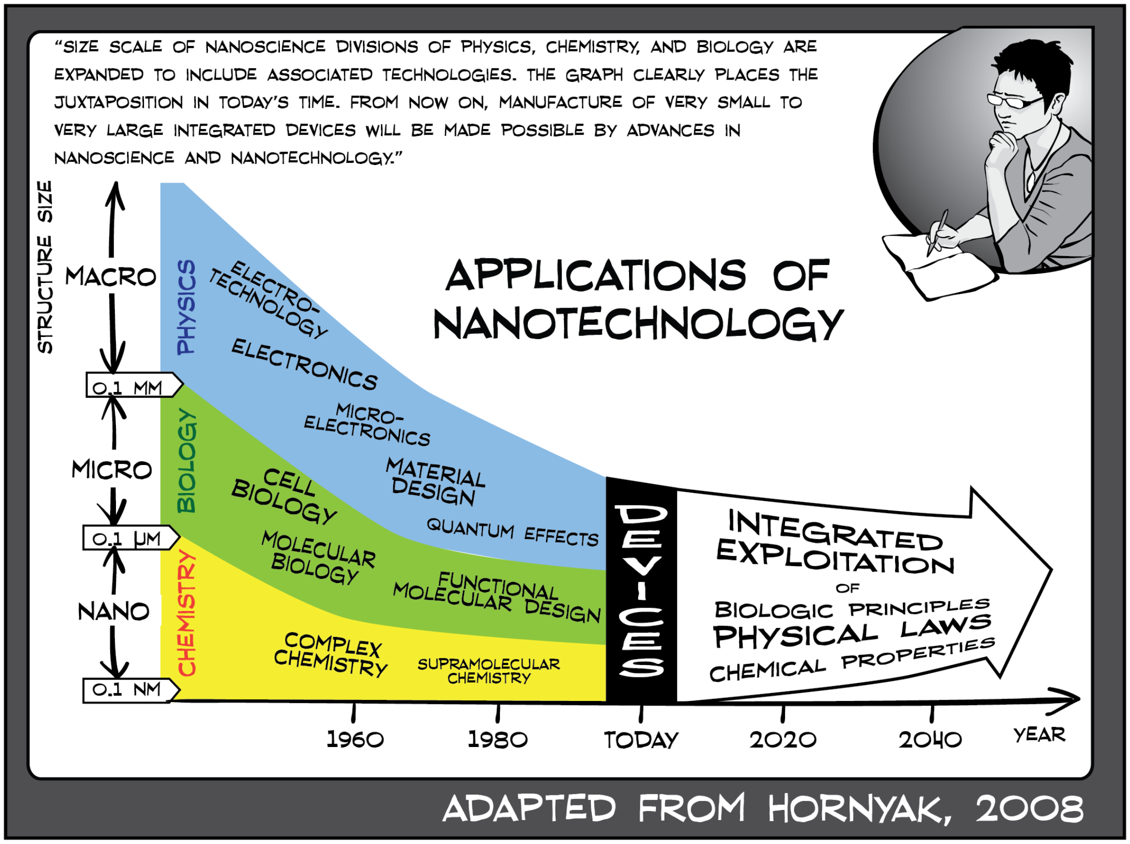

Illustration 55 Applications of nanotechnology along spatial and temporal axes.

Smaller is better is bound up in the ongoing co-production and refiguration of multiple scales of matter (and multiple scales that matter). These scales include not only the size domains of particular technologies, but also the scales of the nanoengineer as a particular profession, nanoengineering as a particular discipline, the Department of NanoEngineering as a particular institution, and the broader social, political, and material worlds that are reconfigured through nanotechnological practices, things, and imaginings.[18]

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18. See Barad *Meeting the Universe Halfway* for a discussion of how scale, understood geometrically, suggests a spatial construction that is inherently exclusionary, whereas a topological analysis emphasizing "connectedness" understands different scales as intra-actively produced. This is particularly

The Moral Dimensions of Learning Scale

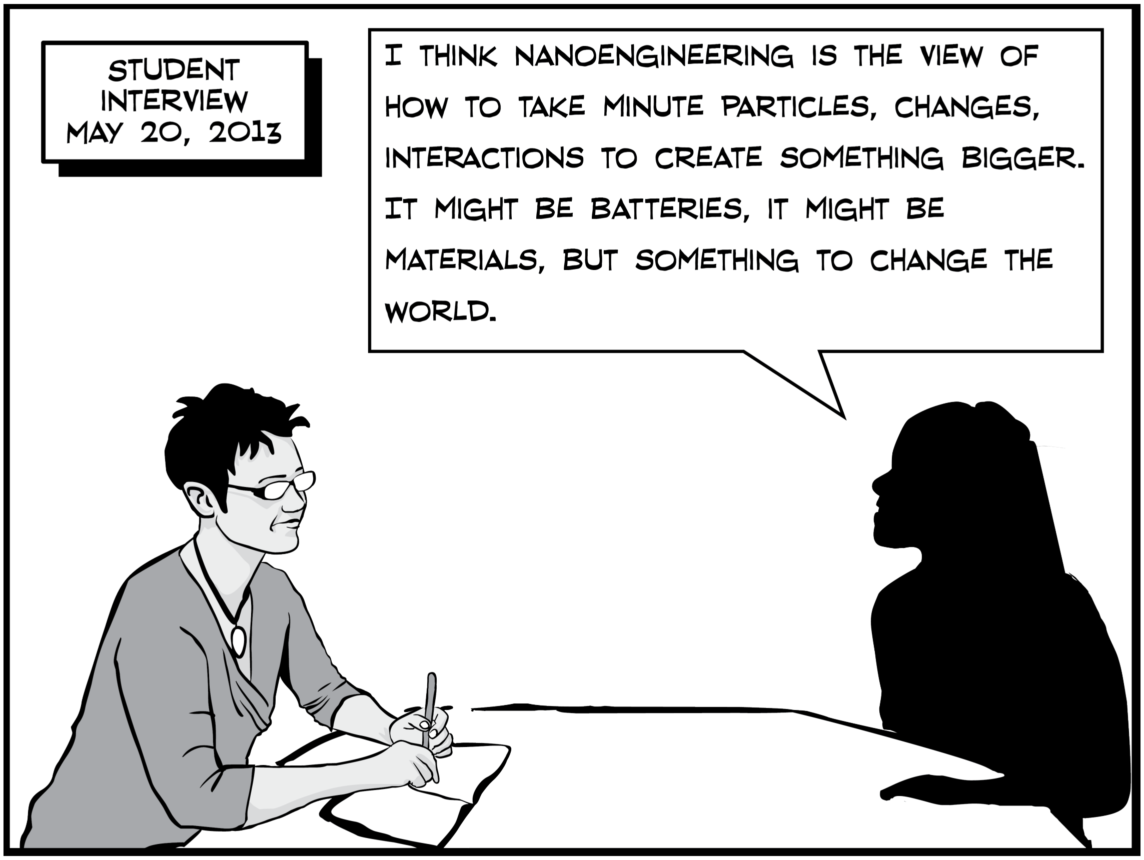

Illustration 56 Emily York: "So at this point how would you define nanoengineering?" Student: "I think nanoengineering is the view of how to take minute particles, changes, interactions to create something bigger. It might be batteries, it might be materials, but something to change the world." Here, "something bigger" refers to larger-scale technologies, such as batteries, but it is also connected to social impact; something bigger is something "to change the world."[19]

I want to briefly describe the moment that alerted me to the moral dimension of the nanoengineering curriculum, highlighting the pedagogical import of how technologies are framed. In one of the lectures in this introductory course, the professor presented

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apropos for thinking about nanoengineering, which is definitionally premised on the uniqueness of the nanoscale, and the ways in which it helps to produce the scales of nanomatter, nanoengineer (the person), nanoengineering (practices/community of practitioners), NanoEngineering (department/institution), nanotechnology industries, and nanotechnology-infused sociotechnical worlds.

19. Interview with NanoEngineering student, May 20, 2013, transcribed by author. In this chapter I have chosen not to use pseudonyms for the students. Each interview cited is with a different student.

nanoscale barcodes as anti-counterfeit tracking technologies for “product tracking and counterfeit testing.”[20] The professor specifically mentioned that they could be useful for “protecting a document” such as a passport, or for drugs such as Viagra, and the lecture slide showed images of cell phones, Nike shoes, and pharmaceutical pills with the caption “Real or Fake?”

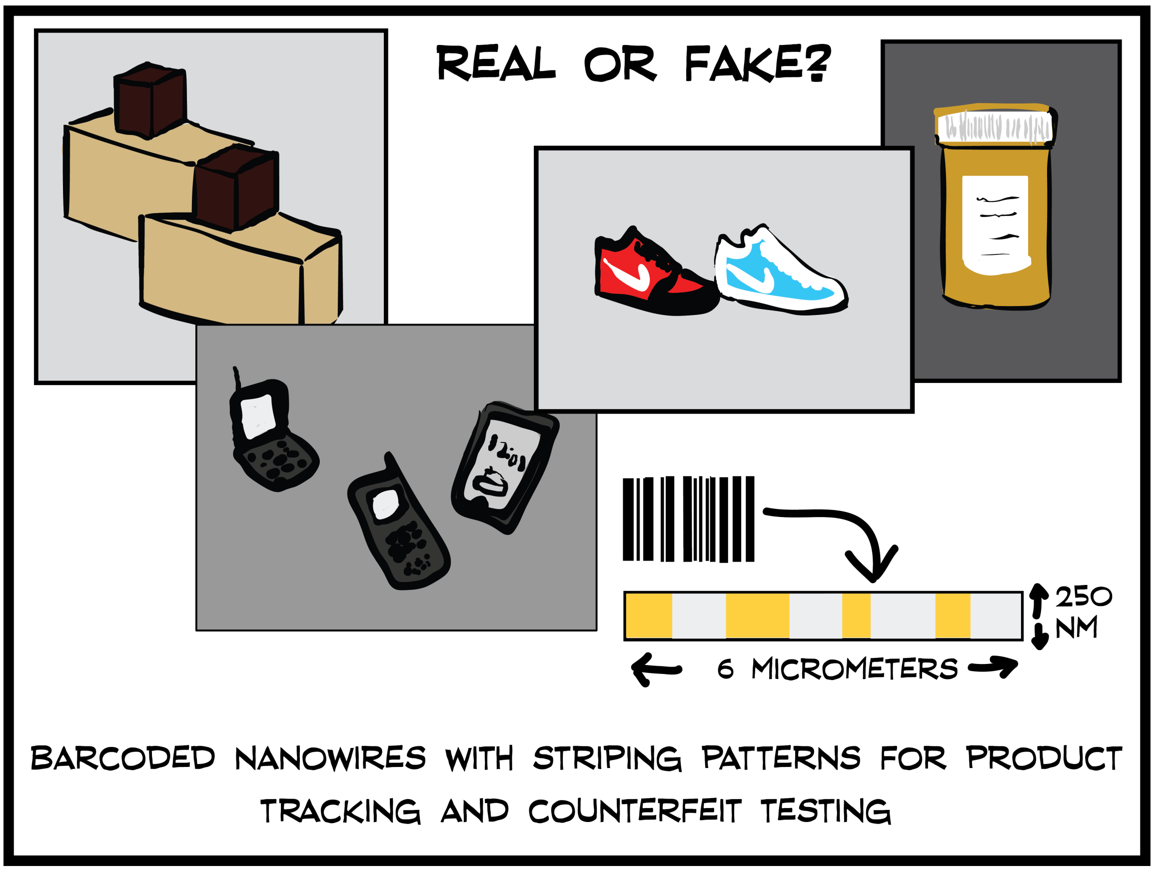

Illustration 57 Nanoscale barcoding.[21]

He additionally indicated that barcodes could be placed on each individual pharmaceutical pill.[22] He presented this innovation as another achievement of

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20. Intro II lecture slide, 2013.

21. Intro II lecture slide, 2013.

nanotechnology and an unproblematic benefit to society. A student raised his hand and asked if it was safe to ingest a pill containing a nanoscale barcode. This struck me because in my observations of eleven undergraduate nanoengineering courses at that point, I had not witnessed another moment in which a student had interrupted the lecture to ask whether a specific nanotechnology was safe. Rather than taking an opportunity to engage this question, the professor said, "Yes" and moved on to the next slide. Another student raised his hand to follow up, reiterating the first student's question. Again, the professor said that it was safe, and moved on. I cannot make any claim about the professor's intentions here, which may have been simply to get through his material before class ended, a familiar predicament for a professor in a classroom. Nevertheless, not engaging these questions became a moment in which he suggested, however inadvertently, that it was unnecessary to explore the possibility that smaller might not be better. This message carried weight in part because it was coming from the professor, an authoritative figure.[23] Moreover, this moment could have been an opportunity to shift from scientific literacy—connoting knowledge of the facts and methods of science—to what Karen Barad calls "agential literacy," or "learning how to intra-act responsibly

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22. I have not independently verified this. In a preliminary search of companies that do RFID tracking for pharmaceuticals, I saw only references to using such devices in pharmaceutical and food packaging, not in individual pills.

23 James Wertsch, "The Multivoicedness of Meaning." In *Discourse Theory and Practice: A Reader*, edited by Margaret Wetherell, Stephanie Taylor and Simeon Yates, 222-35: Sage Publications, 2001. For Bakhtin, authoritative discourse refers to utterances that are fixed, often embodied by authoritative figures such as teachers and pastors. Wertsch, writing about and quoting Bakhtin, writes that, "instead of functioning as a generator of meaning or as a thinking device, an authoritative text 'demands our unconditional allegiance,' . . . It is 'fused with its authority—with political power, an institution, a person—and it stands or falls together with that authority'" (22). This moment is one in which the professor is uttering authoritative speech in relation to the students, even as it is dialogic in relation to broader nanotechnology discourses.

within the world."[24] Barad outlines the ways that scientific literacy is commonly associated with social responsibility: if people possess the former, then they are presumed to be socially responsible.[25] But agential literacy, she argues, requires additional knowledges that include the ability to recognize the boundaries produced through one's own scientific practices and to analyze potential consequences.[26] More generally, social responsibility entails an ongoing practice of thinking about science as part of doing science.[27]

This particular moment in the nanoengineering lecture was a missed opportunity to discuss what kind of research might sufficiently prove that nanoscale barcodes are safe for human consumption, as well as what kinds of policies and regulations may or may not be in place to require such research. It also could have been an opportunity to discuss more broadly the social, political, and economic implications of using nanoscale barcode tracking for a range of items, from pharmaceuticals to food to textiles. Who benefits from such tracking? Who doesn't?[28] One potential downside identified by Jeroen van den Hoven in relation to the similar technology of radio frequency identity chips is that such

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24. Karen Barad, "Reconceiving Scientific Literacy as Agential Literacy: Or, Learning How to Intra-act Responsibly Within the World" in *Doing Science + Culture*, edited by Roddey Reid and Sharon Traweek (New York: Routledge, 2000), 5.

25. Ibid., 227.

26. Ibid., 237.

27. Ibid., 245.

28. Erin Cech, "The (Mis)framing of Social Justice: Why Ideologies of Depoliticization and Meritocracy Hinder Engineers' Ability to Think About Social Injustices" in *Engineering Education for Social Justice: Critical Explorations and Opportunities* (New York: Springer, 2013), 67-84. Not discussing the political here implicitly reinforces the idea that technology is apolitical. See Cech for a discussion of how ideologies of meritocracy and depoliticization within engineering cultures frame social justice issues as "irrelevant to engineering practice" (67).

tracking can turn individuals into “walking repositories of biometric data,” enabling “invisible surveillance” and further threatening privacy.[29] Discussing such questions is important pedagogically, not so much for the answers themselves—which the professor may not have had—as for the practice of critically engaging with the broader contexts of science and innovation, and the implicit encouragement to do so that would be performed by the professor as an authoritative figure.

Smaller Is Better

> *Emily York*: How would you define nanoengineering?
>
> *Student*: I would say it’s designing and synthesizing devices, or nanoparticles on the nanoscale in order to harvest their unique properties in order to benefit some area of humanity.
> — Interview with a fourth-year nanoengineering student, 2014
>
> *Student*: Nanoengineering can be defined as the application of sciences at a new frontier. . . . A lot of it is finding new ways to apply science. . . .We have all this science, how do we apply it to a smaller scale to make things more possible.
> — Interview with a fourth-year nanoengineering student, 2014
>
> *Student*: I would say it’s designing and synthesizing different devices, or nanoparticles that are on the nanoscale in order to harvest their unique properties in order to benefit some area of humanity, or just research, it doesn’t have to be direct benefit, but fundamental research is also very important.
> — Interview with a fourth-year nanoengineering student, 2014

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29. Jeroen Van den Hoven, "Nanotechnology and Privacy: Instructive Case of Rfid," Chap. 19 in *Nanoethics: The Ethical and Social Implications of Nanotechnology*, edited by Fritz Allhoff (Hoboken, NJ: Wiley-Interscience, 2007), 255.

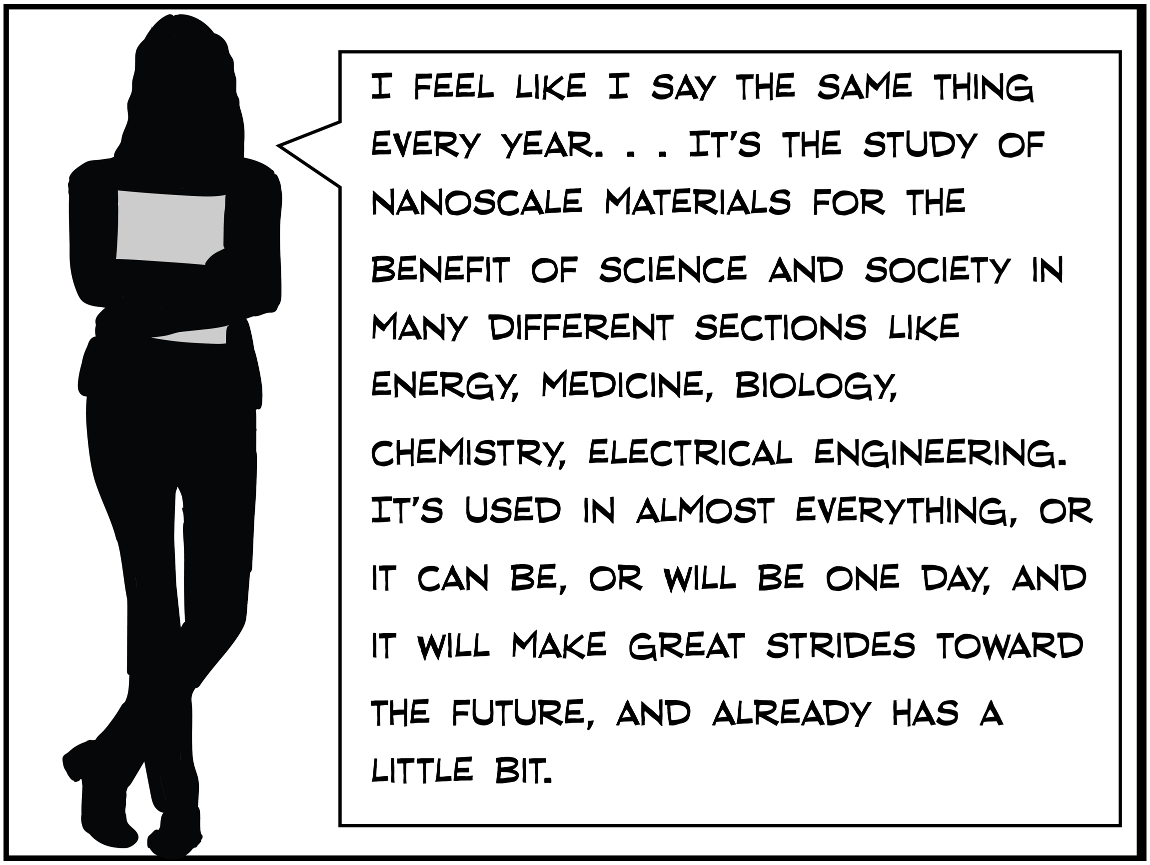

Illustration 58 NanoEngineering student: "I feel like I say the same thing every year. . . . It's the study of nanoscale materials for the benefit of science and society in many different sections like energy, medicine, biology, chemistry, electrical engineering. It's used in almost everything, or it can be, or will be one day, and it will make great strides toward the future, and already has a little bit."[30]

Nanoengineering students learn over the course of four years to define nanoengineering in terms of size as well as benefits. I begin my analysis with the first lecture of the course, which introduces scale as both disruptive and continuous. The theme of disruption and continuity plays out over multiple slides. The nanoscale is presented as a static and ontologically distinct nano world that offers revolutionary possibilities due to its unique behaviors and properties. Yet its continuity with meso and macro scales is communicated through references to miniaturization and shrinking, and to

30. Interview with fourth-year NanoEngineering Student, April 21, 2014, transcribed by author.

comparisons with objects on other scales. Nanoengineering thereby becomes conceptualized as “engineering, just on a very small scale.”[31] This allows the implicit message of *smaller is better* to be nimble; the promise of disruption is made safe by the guarantee of continuity.[32]

For instance, one PowerPoint slide with the caption “Nano is all about size” highlights continuity through its comparisons of a house (“10 m”), an ant (“2 mm”), and a gold nanoparticle (“2 nm”):

31. Though students I interviewed had a variety of responses when I ask them to define nanoengineering, they most commonly included some version of “engineering on a very small scale,” regardless of whether the student was in her first, second, third, or fourth years.

32. Alfred Nordmann, “Enhancing Material Nature,” in *Nano Meets Macro: Social Perspectives on Nanoscale Sciences and Technologies*, edited by Kamilla Lein Kjølberg, and Fern Wickson (Singapore: Pan Stanford Publishing, 2010), 283-306. The discourse that produces the dual identities of disruption and continuity in reference to scale does similar political work as that which claims nature as a nanotechnologist and nanotechnology as natural—fitting together the promise of revolutionary innovation with the security of incremental progress and/or progress that fits within a natural order. See Nordmann for a discussion of the construction of “with nature beyond nature.”

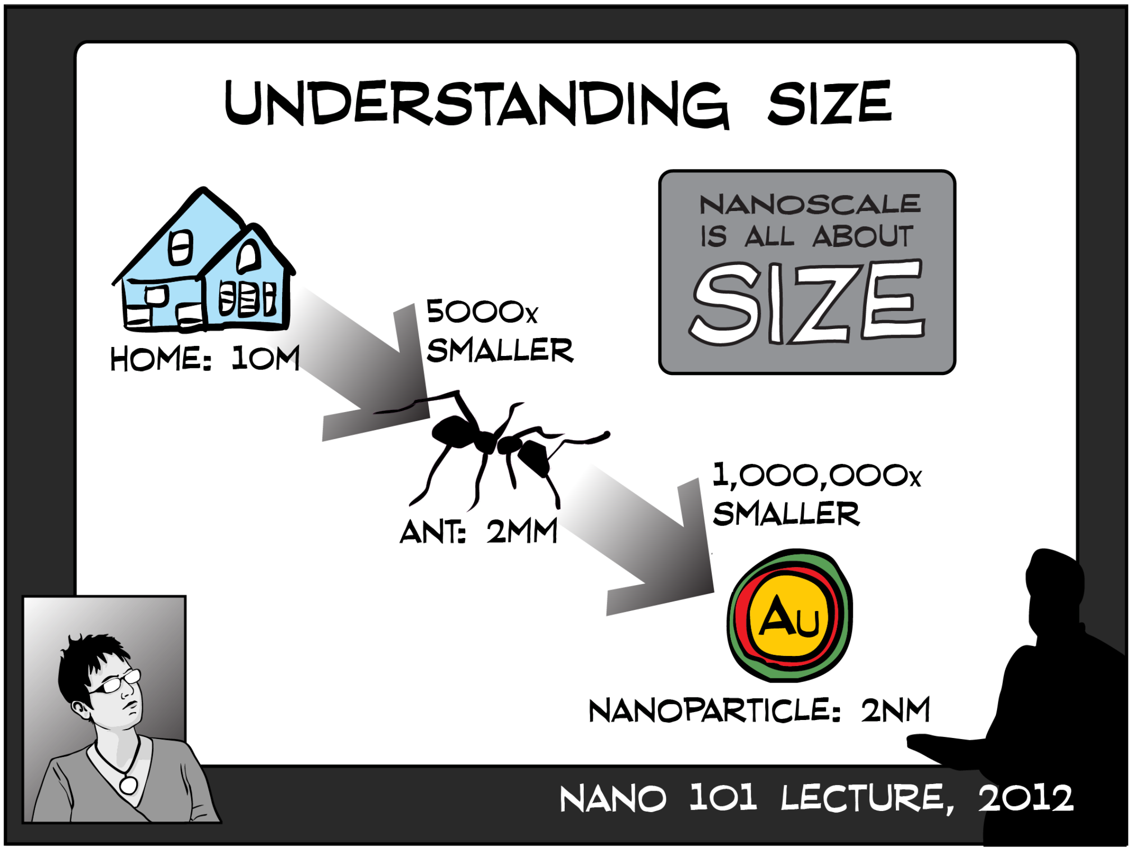

Illustration 59 Understanding size.

It also shows the relationship between these items: the house is 5,000 times larger than the ant, and the ant is 1,000,000 times larger than the nanoparticle.[33] The slide emphasizes both the extraordinariness *and* the ordinariness of the nanoscale: the gold nanoparticle is unfathomably small but nevertheless in a continuum with ants and houses. Importantly, it *exists*, as much as either an ant or a house does, even though it cannot be directly perceived.

33. Zach Horton, "Collapsing Scale: Nanotechnology and Geoengineering as Speculative Media," n *Shaping Emerging Technologies. Governance, Innovation, Discourse*, edited by Kornelia Konrad, Christopher Coenen, A.B. Dijkstra, Colin Milburn and Harro van Lente (IOP Press, 2015), 203-18. See Horton for a discussion of how such visual juxtapositions enact a "scalar collapse" that privileges the scale of the human.

This slide exemplifies the ways in which the production of a nanoengineering identity in the college classroom is in a dialogic relationship with broader discourses about nanotechnology. From a Bakhtinian perspective, the slide is itself a heteroglot utterance, a discursive element that both responds to previous utterances and anticipates a response.[34] As such, it contains traces of the "socio-ideological consciousness around the given object" and constitutes "specific points of view on the world."[35] Comparing nano to everyday objects—even specifically an ant and a house—and relating these scales in terms of orders of magnitude are shared practices within the broader nanotechnology community.

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34. Bakhtin, *The Dialogic Imagination*.

35. Ibid., 276, 294.

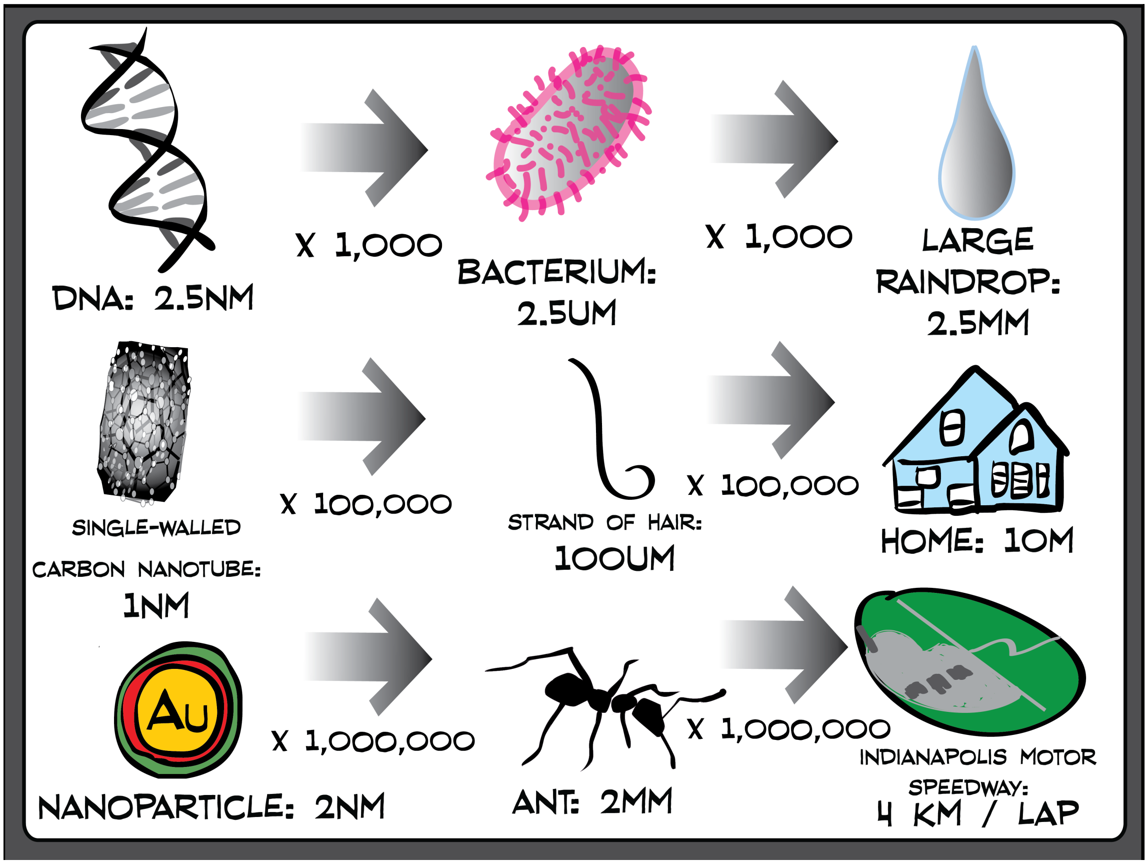

Illustration 60 NNI "The Scale of Things." [36]

For example, the NNI has a diagram that similarly relates the sizes of similar objects, including an ant, a house, and a nanoparticle. The lecture slide as an utterance visually contains the traces of languages and practices of nanotechnology beyond the classroom.

Justifying Nano

The first lecture also repeatedly alternates between "what" and "why" slides, forming a dialogic relationship between the two that conflates definitions of nano with justifications of its use. For example, following a "what" slide that communicates size

36. Based on an image posted on the NNI's website: http://www.nano.gov/nanotech-101/what/nano-size, accessed March 15, 2016.

through scale comparison, the subsequent “why” slide provides the following three answers: nano “represents revolution,” its size results in “unique properties and behaviors,” and it will result in “far-reaching outcomes.”

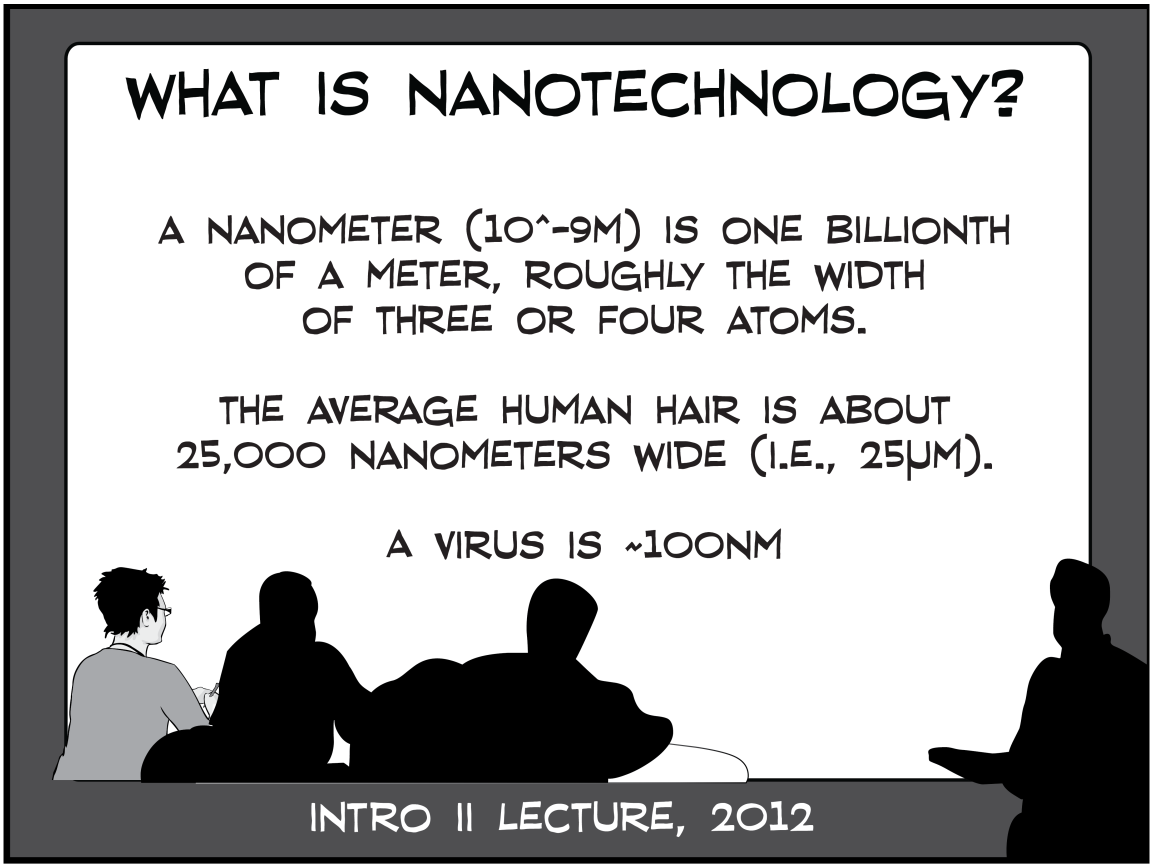

Illustration 61 What is nanotechnology? Intro II lecture slide, 2012. “A nanometer (10 ^-9) is one billionth of a meter, roughly the width of three or four atoms. The average human hair is about 25,000 nanometers wide (i.e., 25 micrometers). A virus is ~100nm.”

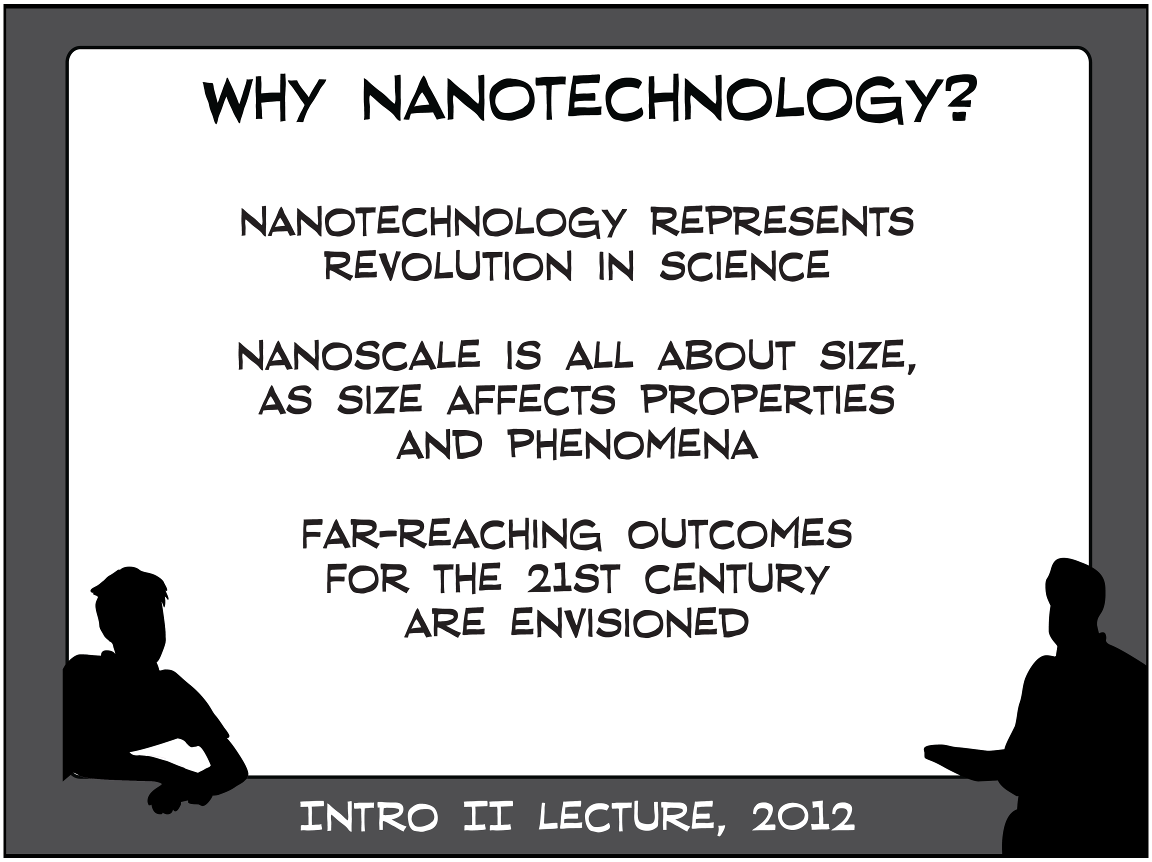

Illustration 62 Why nanotechnology? Intro II lecture slide, 2012. "Nanotechnology represents revolution in science. Nanoscale is all about size, as size affects properties and phenomena. Far-reaching outcomes for the 21st century are envisioned."

While the "what" suggested continuity by articulating the nanoscale in terms of larger scale objects , the "why'" suggests disruption. The very fact that nanotechnology "represents revolution" appears as its own justification while "far-reaching outcomes" hitches the future macroworld to the present nano world. In the juxtaposition of "what" and "why," *smaller* begins to anticipate *better*.

The next "what" slide contains two parts:

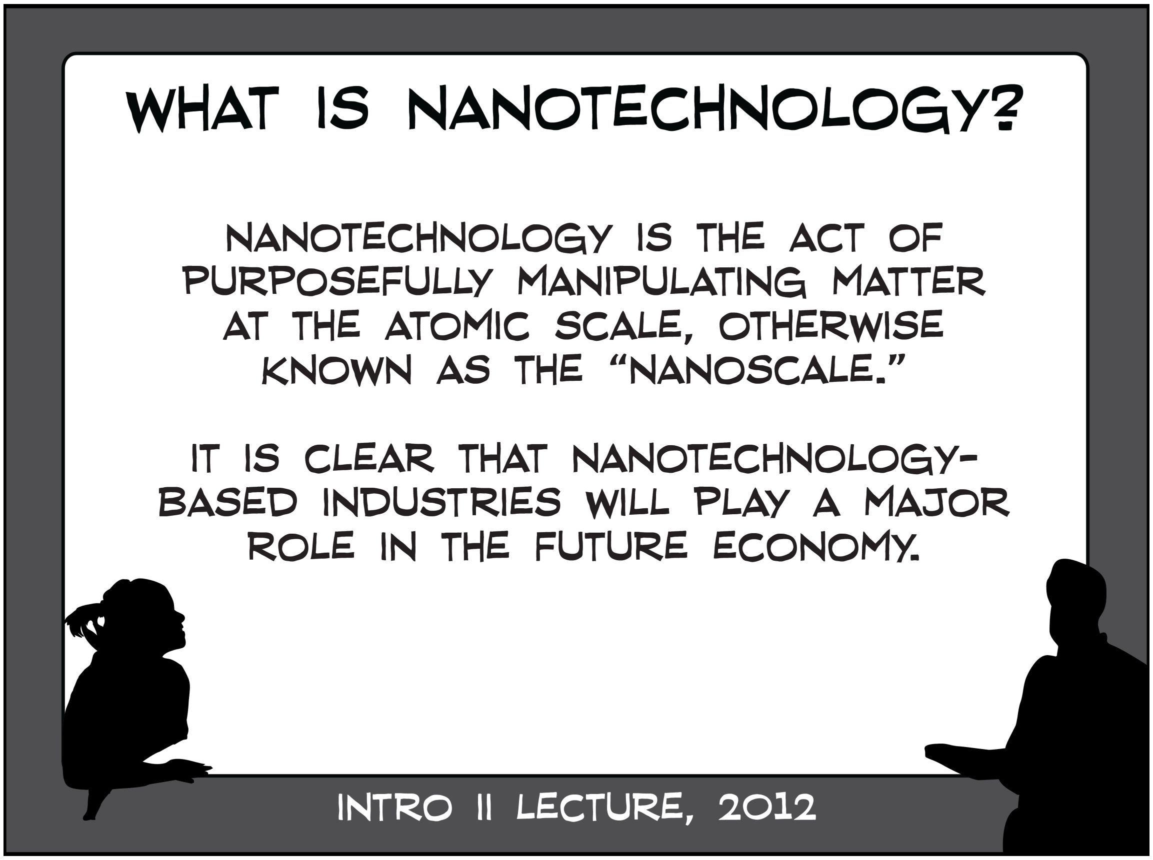

Illustration 63 What is nanotechnology? Intro II lecture slide, 2012. "Nanotechnology is the act of purposefully manipulating matter at the atomic scale, otherwise known as the 'nanoscale'," and "It is clear that nanotechnology-based industries will play a major role in the future economy."

Here—echoing the earlier definition of nanotechnology from the NNI—there is no meaningful distinction between doing nanoengineering and the resulting nanotechnology materializations. Such rhetorical slippages cross spatial and temporal scales. The "act of purposefully manipulating matter at the atomic scale" is followed by the "future economy," connecting the nano world/present with the macro world/future.

Another "why" slide contains three answers:

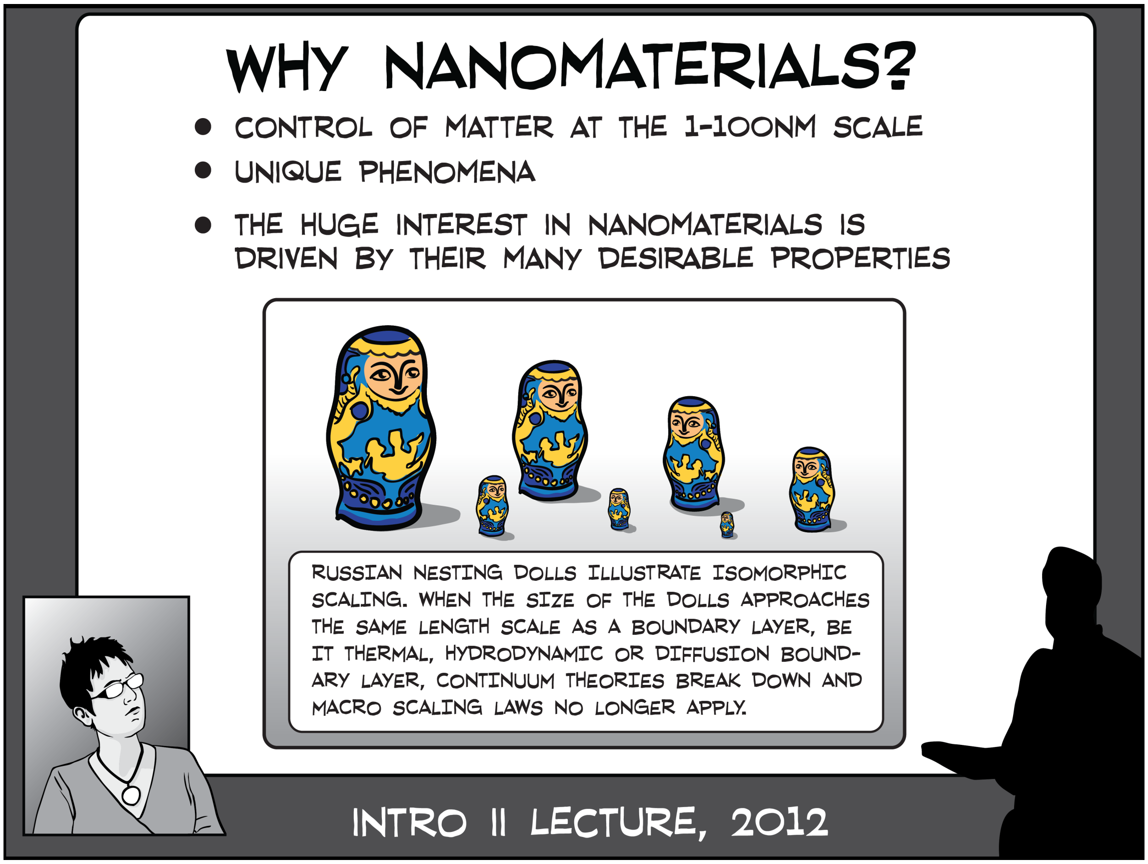

Illustration 64 Why nanomaterials? Intro II lecture slide, 2012. "Control of matter at the 1-100 nm scale," "Unique phenomena," and "The huge interest in nanomaterials is driven by their many desirable properties."

This is followed by a picture of Russian nesting dolls, with the description:

> Russian nesting dolls illustrate isomorphic scaling, when the size of the dolls approaches the same length scale as a boundary layer, be it thermal, hydrodynamic or diffusion boundary layer, continuum theories break down and macro scaling laws no longer apply.[37]

"Control of matter"—language widely used in nanotechnology discourse, as I discussed in Chapter 2—suggests that control is its own end, situating nanoengineering within a

37. Intro II lecture slide, 2012.

long Western history of aspiring to control the material world.[38] The second and third answers suggest that the ontological disruption that creates "unique phenomena" is necessarily desirable and therefore drives the "huge interest" in nanomaterials, again previewing the theme that smaller is better. The image of the Russian dolls and accompanying description demonstrate how easily continuity and disruption sit side by side. They visually communicate the continuity and fundamental sameness of materials at different scales, where each successively smaller doll fits within the larger one. The set suggests that scale as objectified in things is distinct and static. However, eventually, if you go small enough, there is something that can no longer count as a Russian doll. This is the limit case of Russian dolls, just as nanoscale matter represents the limit case of macroscale matter. The text accompanying the image explicitly indicates a fundamental disruption: "continuum theories break down and macro scaling laws no longer apply."

These first slides connect the nanoscale to a mode of world-making that sees its purpose and justification as emanating directly from its material base, even as this material base is inhabited by the promises and dreams of its manipulators.[39] Following this first lecture introducing scale, the primary focus of the second lecture is to introduce students to the scaling laws. However, since the second lecture is previewed in the first and recapped in the third, the students encounter the scaling laws over the course three

38. Feynman, "There's Plenty of Room." Recall that the NNI's vision invokes the language of controlling matter, and Feynman's speech also refers to the "problem of manipulating and controlling things on a small scale" (1).

39. NanoEngineering Department, "Mission Statement," accessed September 24, 2014, http://nanoengineering.ucsd.edu/about-us/mission-statement. This is further evidenced by the departmental website: "[Nanoengineering] attempts to manipulate the 'growth' of materials on the nanometer scale, mimicking the processes of nature, which could potentially lead to a vast array of revolutionary materials and products that would benefit all other aspects of engineering, medicine, and other technologies, and everyday life" That is, the products of this worldmaking will be ubiquitous and, by definition, good.

lectures, spanning a week and a half. Here, the professor revisits the basics of scale, shows how the scaling laws can predict size-contingent properties and behaviors at the nanoscale, and poses scale-conversion problems that involve different spatial or temporal units of scale and orders of magnitude. The professor covers many of these problems in class, repeatedly tells student to practice them, assigns them for homework, and includes them on the first exam.

Making Benefit Benign

The title of the first slide, "Scaling Laws," is followed by explanatory text:

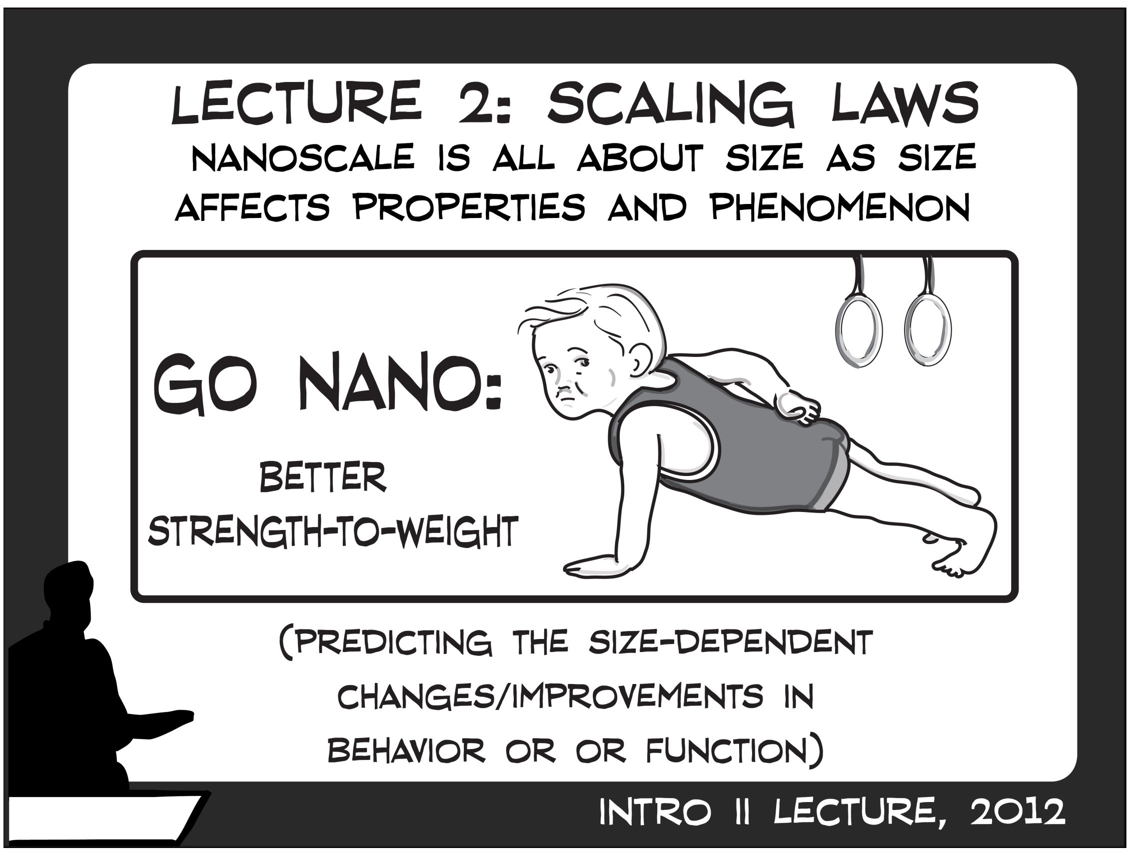

Illustration 65 Scaling laws. Intro II lecture slide, 2012. "Nanoscale is all about size as size affects properties and phenomenon" [*sic*]. The text is followed by pictures of a strong baby boy doing a one-armed pushup and a small male weight lifter hefting a large dumbbell with the caption "Go Nano: Better Strength-to-Weight." Underneath the pictures is a parenthetical gloss: "(Predicting the size-dependent changes/improvements in behavior or function)."

Note first how the slide frames the subject technically: it describes the relationships between scale and properties/behaviors as "laws," and it locates the promise of the nanoscale in the predictability of these relationships. Yet by showing the inverse relationship between size and strength using playful images that connote innocence, safety, and desirability, the slide visually suggests that increased strength-to-weight ratio is a benefit.[40] The normative stance that *smaller is better* is also established in this slide in the imperative to "go nano." It insists that the reason to manipulate matter on the nanoscale is "*better* strength-to-weight ratio." "Better," rather than a neutral modifier such as "increased" suggests this is necessarily positive. This stance is even further clarified in the parenthetical gloss at the bottom of the slide, where the slash in "changes/improvements" indicates that "size-dependent changes" *are* "size-dependent improvements." Going smaller—specifically, going nano—is better.

Rendering Nano Natural and Universal

The next slide articulates nanoengineering as a biomimetic practice, contextualizing the scaling laws within technical, moral, social, and political valences.

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40. I observed this class two years in a row, and both times, this image evoked laughter by the students.

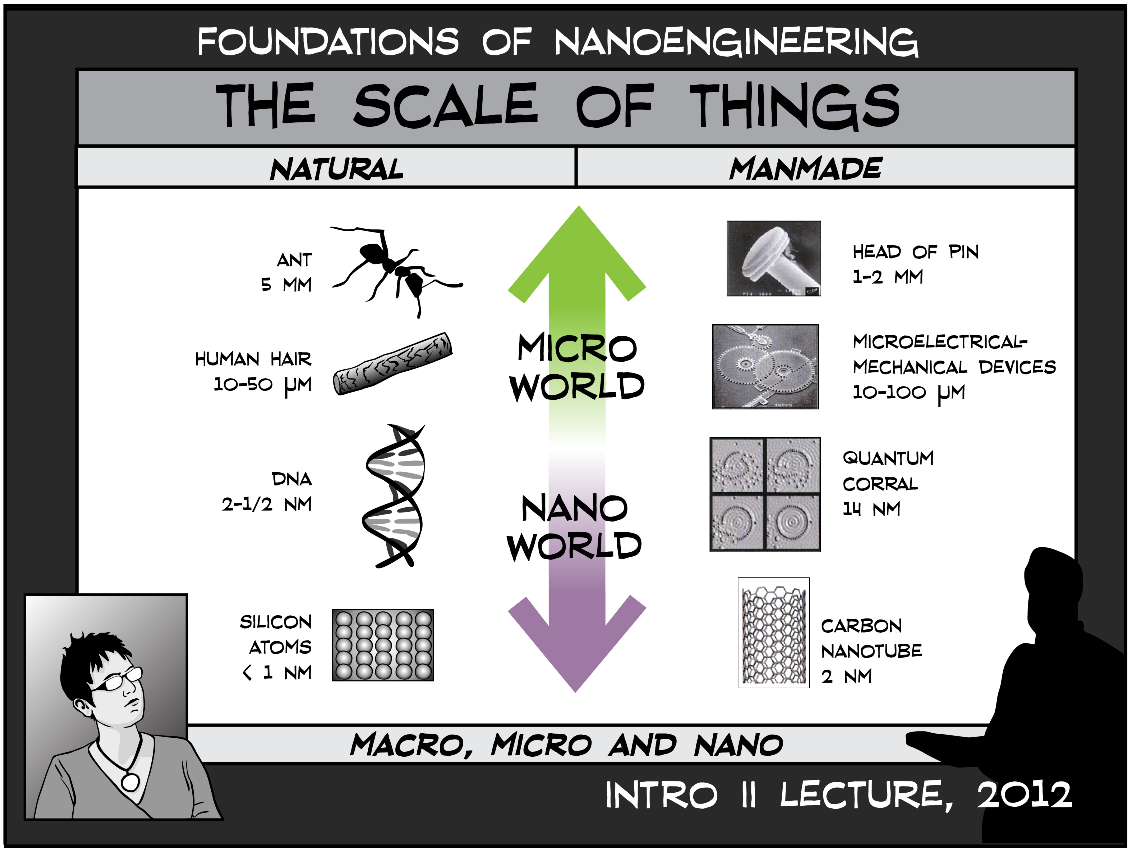

Illustration 66 The scale of things. Intro II lecture slide, 2012. Author invokes fair use of images on right side, which are from the original slide.

This image of "The Scale of Things" is widely used in the department, displayed on multiple department walls and used in other courses.[41] The table juxtaposes "natural" materials on the left with "manmade" materials on the right, and the vertical up and down arrows represent a continuum between the "Nano World" toward the bottom and the "Micro World" toward the top. Objects such as the ant and the pin are distinguished as natural or manmade but linked by size. Placing these categories side-by-side draws on the moral authority of nature by presenting human manipulation of the material world as

41. The label again signals a connection to the previously referenced NNI image. Though the things represented are different, both images include pictures of "natural" and "manmade" objects.

natural and universal. It simultaneously suggests that the natural world is technological. In terms of comparison, the objects are evacuated of content or meaning—what is relevant in the comparison is precisely the irrelevance of what these things are: the object itself is implicitly presented as neutral. This is important in producing the notion that *smaller is better* because, as an abstract statement of fact, it is indifferent to the specificity of the object. Universalism is further implied by the statement next to the image: "21st century challenge [:] Assemble nanoscale building blocks to make functional devices." In the context of a department that labels the beneficiary of nanotechnologies as either "humanity" or "society," both *the* challenge and *the* solution are understood as universal categories. This language is widely invoked in nano discourse. For example, the NNI says, "Applications of nanotechnology are delivering in both expected and unexpected ways on nanotechnology's promise to benefit society."[42]

The scale-conversion problems that students are asked to solve entail converting between different scalar units—both spatial and temporal—to rethink everyday, ordinary things in terms of scale. These things are sometimes common and familiar, such as the campus library or a local bridge, and sometimes more abstract, such as human lives or just the units themselves, for example, "1 gallon."

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42. National Nanotechnology Initiative, "Nanotechnology Benefits," accessed August 2, 2014, http://nano.gov/you/nanotechnology-benefits.

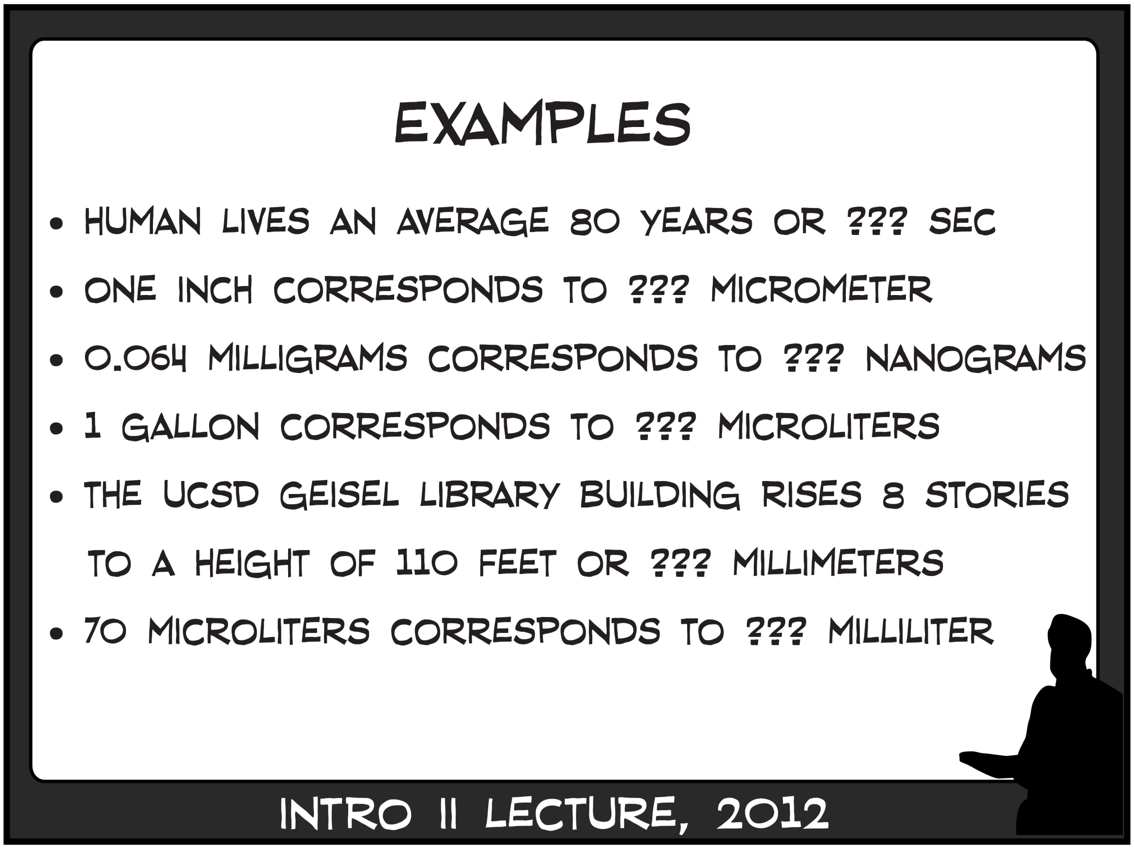

Illustration 67 Scale conversion problems.

As in the previous image “The Scale of Things,” the objects themselves are made irrelevant. The professor extensively addresses many of these problems, admonishing the students to practice similar problems at home. The students repeatedly traverse spatial and temporal scales, moving from nano to micro to macro and back again, memorizing how many zeros to add or subtract as they determine how many seconds make up 80 years (an “average” human life), or how many millimeters equals 110 feet or 8 stories (the height of the campus library). These problems help to create a naturalized, embodied relationship to scale and scale conversion, where students become adept at converting between different units, thinking different scales in relation to each other, and understanding these scales in terms of everyday experiences. This is not to say that it necessarily achieves the goal of making students feel a naturalized, embodied relationship to the nanoscale. In interviews, students consistently related difficulty in conceptualizing or communicating the nanoscale aside from repeating the kinds of comparisons they've been taught, for example, how many nanometers comprise a dimension of a virus or a human hair. Yet note how this embodied relationship to scale is produced through local points of reference: the campus library, or an "average" lifespan of 80 years—which is the lifespan of particular human bodies, not a universal one. The knowledge being produced is situated, and the traces of this situated knowledge are inscribed in the problems that help students conceptualize and traverse scale.[43]

In the next slide, the lecture moves from the ordinary objects of scale-conversion problems back to the technical, moral, and sociopolitical implications of these scale traversals.

43. Every student whom I've asked has confirmed that these problems presented no challenge, mathematically. These students had already taken rigorous mathematics and physics classes, and most of them described the task of calculating the height of the campus library in millimeters as "easy". To be sure, based on my observations in a nanoengineering laboratory that chemically synthesizes nanostructures, it seems clear that such laboratory work frequently requires scale-conversion calculations and that this is a basic skill that students need. Yet for a week and a half, much of the students' in-class work, homework, and midterm examination is focused on these problems. It was for this reason that I asked the professor about his goal for these lectures on scale and scale-conversion problems, and why I ultimately decided to look more closely at what work they were doing.

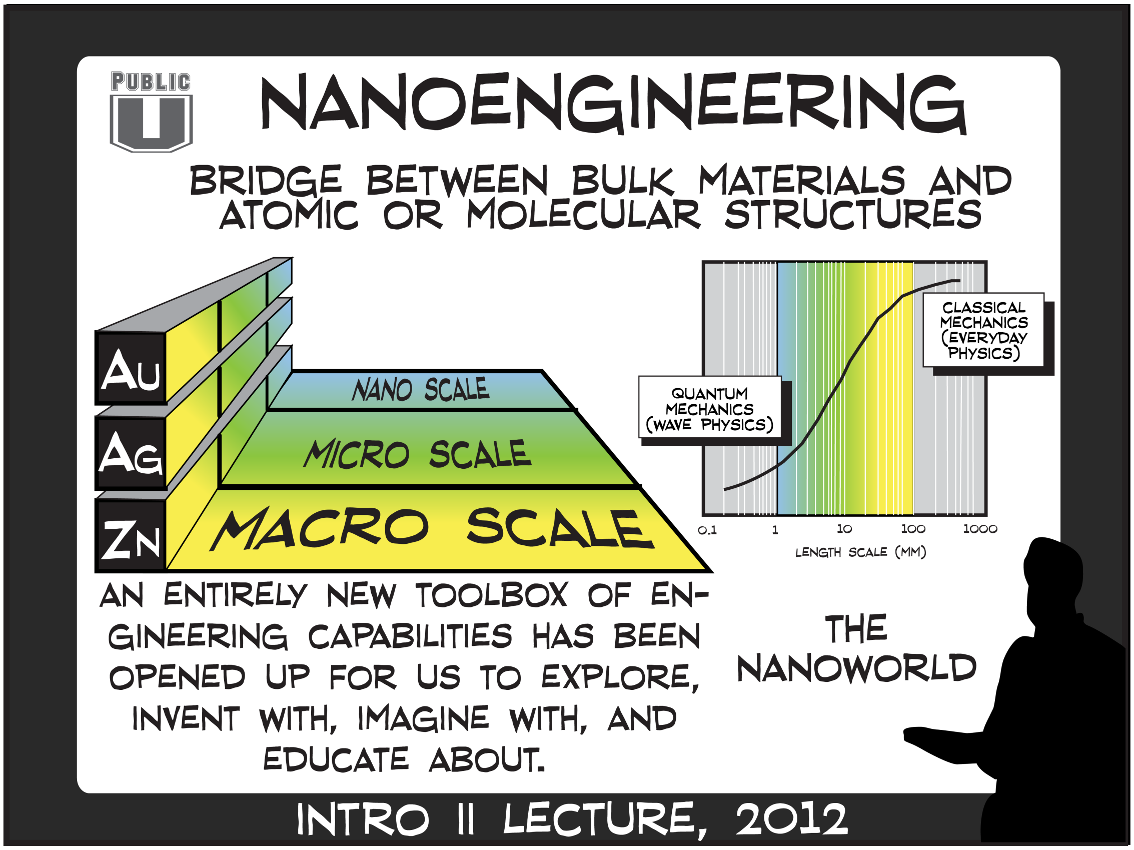

Illustration 68 Three dimensional periodic table. The slide presents an image of a three-dimensional periodic table with the labels "macroscale," "microscale," and "nanoscale."

This slide visually demonstrates that as the third dimension scales down from macro to nano, the element becomes fundamentally different—emphasizing again the ontological differences between materials at the nanoscale and their "bulk" counterparts. The title of this slide below the institutional label tells the students that the nanoscale is a "bridge" between bulk and atomic scales. To the right of the periodic table is a graph labeled "The Nanoworld" that ranges from 1 to 100 nanometers, showing that matter on the low end adheres to quantum mechanics and on the upper end to classical mechanics—hence, the metaphor of the bridge. Text in the lower left corner states, "An entirely new toolbox of engineering capabilities has been opened up for us to explore, invent with, imagine with, and educate about." I understand this phrase within the "socio-ideological consciousness" produced in part by the history of nanoengineering as told through lectures and media in the nanoengineering curriculum.[44] The indirect phrasing ("has been opened up") makes sense within an understanding of nanoengineering and the nanoscale as something that is billions of years old (as enacted by Nature[45]), but that was first articulated by Feynman in his 1959 speech, imagined publicly in the 1966 Hollywood film *Fantastic Voyage*, and ultimately developed over the 1980s and 1990s by engineers in industry and academia.[46]

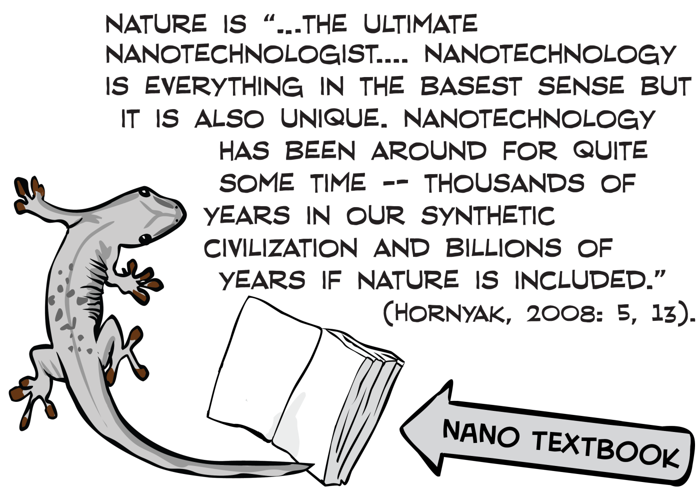

Illustration 69 Nature is "the ultimate nanotechnologist…. Nanotechnology is everything in the basest sense but it is also unique. Nanotechnology has been around for quite some time—thousands of years in our synthetic civilization and billions of years if nature is included."[1]

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44. On "socio-ideological consciousness," see Bakhtin, *The Dialogic Imagination*, 276.

45. Gabor Hornyak, Gabor, *Introduction to Nanoscience*, Boca Raton: CRC Press, 2008. This phrasing in used in a textbook in the curriculum (5, 13), but is also articulated in classroom contexts where, for example, geckos are invoked to demonstrate "nano" in nature.

46. This historical timeline is similar to the one used by the National Nanotechnology Initiative (NNI). However, in my field site, *Fantastic Voyage* is presented as an important element, situated between Feynman and Moore's law, whereas it is not included by the NNI. See National Nanotechnology Initiative, "Nanotechnology Timeline," accessed August 3, 2014, http://nano.gov/timeline .

In this same second lecture on scaling laws, students are reminded of these key developments, with one slide ("From 'Nano-dreams' to Reality") containing the text "Nano Giants and Discoveries" and pictures of Feynman and Richard Smalley. Within this department and its undergraduate major, as shown in Illustration 67, the nanoscale is understood as a "new toolbox of engineering capabilities" that are ready-at-hand, available for exploration, invention, imagination, and education. The "us" in the slide's text suggests the same universalism as the frequent references to "humanity" and "mankind." Yet the nano world as playground and toolbox is produced specifically as the domain of the nanoengineer.

Translating Technical to Social

Another slide further suggests that the implications of the scaling laws are as simplistic and technical as the scaling laws themselves. "Scaling laws are extremely simple observations about how physics works at different sizes," is followed by: "Scaling laws explain why technology based on nanoscale devices is expected to be extremely powerful compared to large-scale machines." Here, the future-oriented expectation of powerful technologies is presented as a self-evident conclusion based on the first statement. The slide continues: "Such laws illustrate the benefits of tiny dimensions with regard to speed of operation, power density, functional density, and efficiency—four very important factors in the performance of any system." The word "benefits" is highlighted, and the text presumes that characteristics such as "functional density"—the multiplication of functions in a single device, as in a smart phone—represent unproblematic social benefits.

Goodwin has shown that such rhetorical practices of highlighting—"making specific phenomena in a complex perceptual field salient by marking them in some fashion"—help to cultivate professional visions, "socially organized ways of seeing and understanding events that are answerable to the distinctive interests of a particular social group."[47] In a slide titled "Introduction to Miniaturization" with the subtitle (in bigger font than the primary title) "The Smaller the Better!" the text highlights specific words in a way that performs this generalizing movement toward the claim of social benefit:

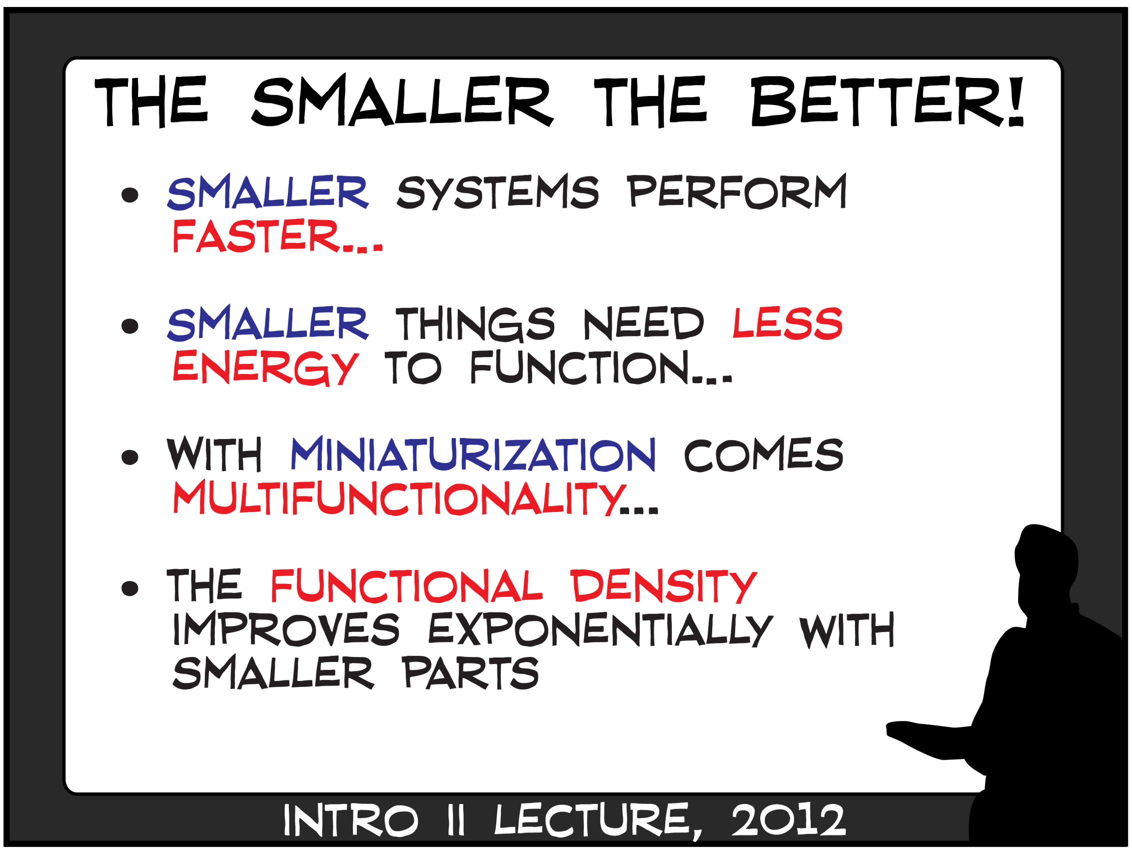

Illustration 70 The smaller the better! Intro II lecture slide, 2012. "Smaller systems perform faster because they have less mass. . . . . The enhanced speed leads to products that perform faster. Smaller things need less energy to function, and such lower power consumption is crucial. . . . With miniaturization comes multifunctionality. For example . . . Functional density."

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47. Goodwin, *Professional Vision*, 606.

While the specifications of smaller and better are technical, highlighting emphasizes smaller-faster-faster-smaller-less energy-miniaturization-multifunctionality-functional density. There are also several slides that return more explicitly to the theme that smaller is different, where different is defined as what makes it better. For example, in one slide the word “Different” is followed by the parenthetical “(better),” and in another, “changes” and “improvements” are connected by a slash. While the professor uses language that communicates benefit in technical terms, by frequently dropping these qualifications, as well as framing and highlighting, he reinforces the abstract principle that smaller *is* better.

The lecture on scaling laws concludes with the anticipatory language of 21st-century expectations for nanotechnology:

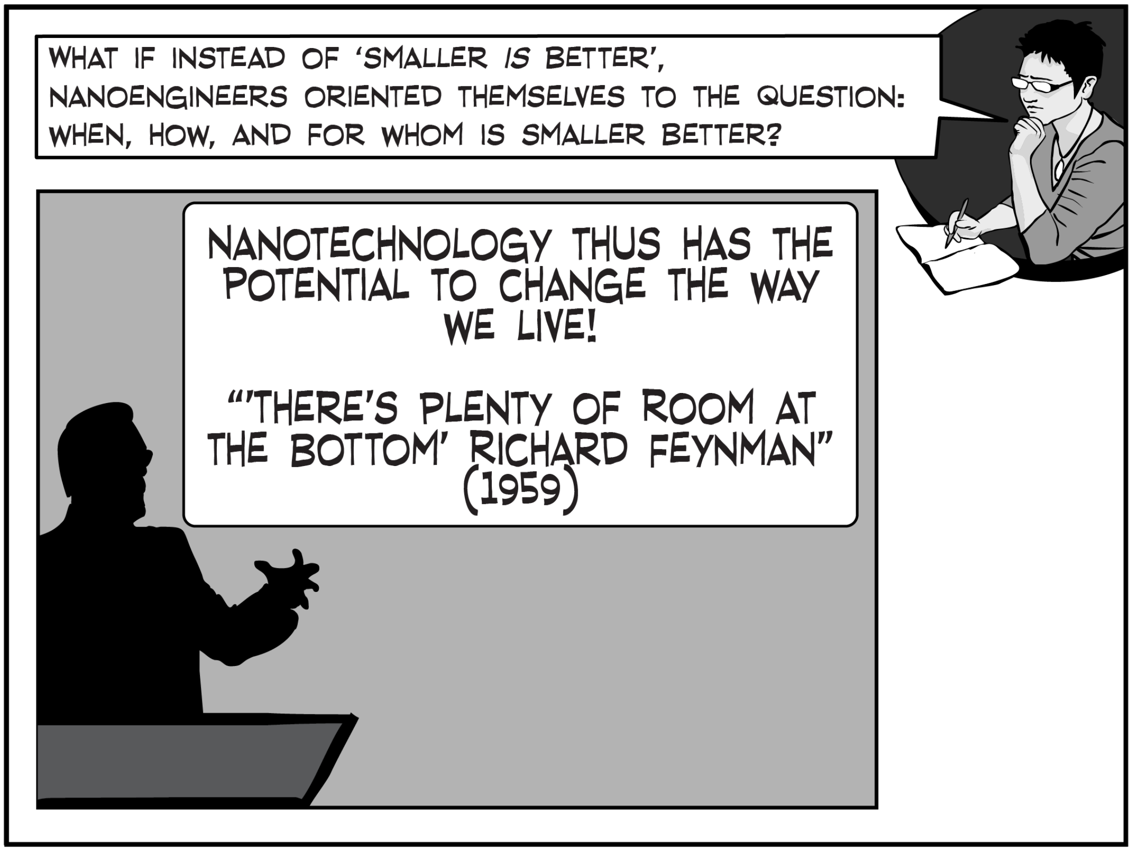

Illustration 71 Change the way we live.

The full text of the lecture slide states,

> Remarkable developments are expected in the 21st century in both scientific knowledge and a wide rage of technologies in most industries, healthcare, electronics, energy, biology, or environment. Nanotechnology thus has the potential to change the way we live![48]

This passage is followed by empty space, and then, at the bottom of the slide: "'There is Plenty of Room at the Bottom' Richard Feynman (1959)." The emphasis on smaller/different/better as it relates to behaviors/properties here aligns with promise and possibility, circling from present to future, and in the end, back to the past. These lectures

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48. Intro II lecture slide, 2013.

form a kind of response to Feynman, who is positioned in lectures, slides, and one of the textbooks as a kind of prophet. A dangling signifier, this last reference to Feynman and his speech seems to connect the predictive power of the scaling laws with the predictive power of Feynman himself. It also reaffirms the moral authority of the professor and the department in claiming that nanotechnology has the potential to change the way “we” live. Over the course of these lectures, better references both technical and social aspects. “Better” can mean more efficient, improved functionality, faster, and increased strength-to-weight ratio—and these are the characteristics the professor is usually explicitly referring to. But it also means that when it changes “the way we live,” that will be better.

When, How, and For Whom Is Smaller Better?

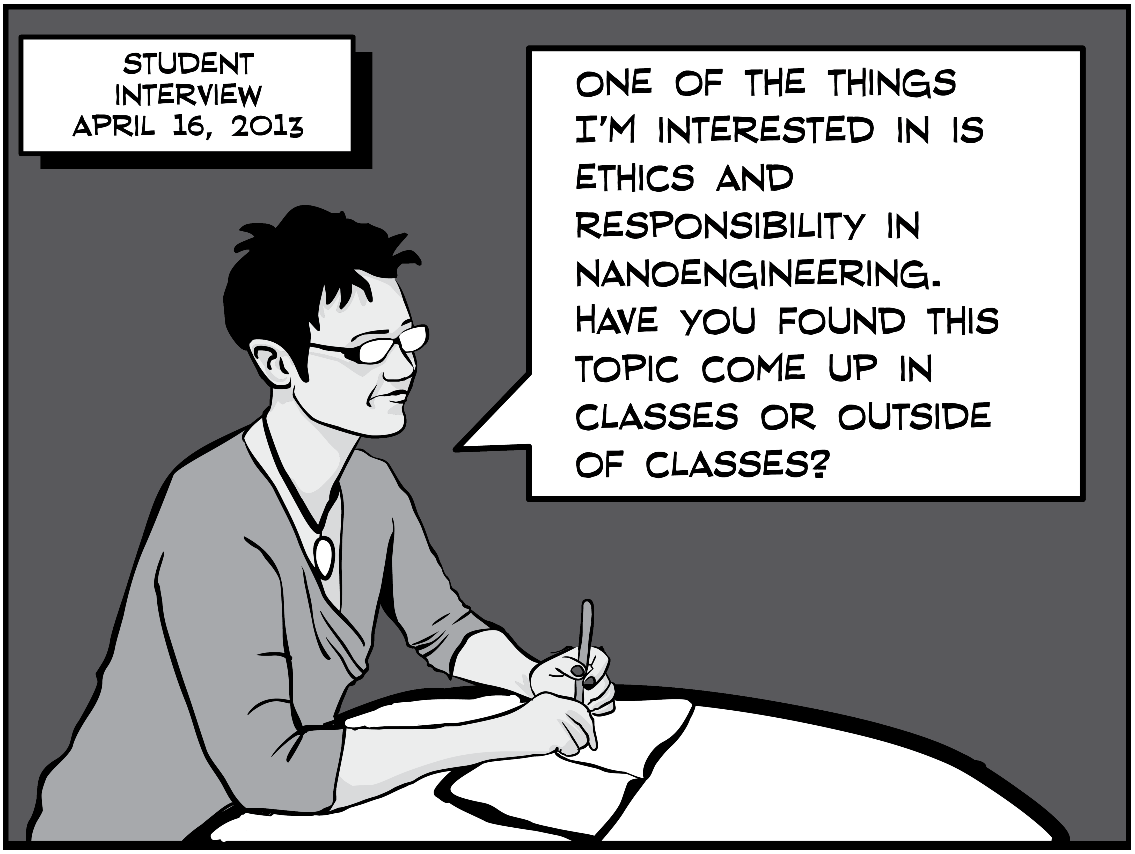

Illustration 72 I ask a student: "One of the things I'm interested in is ethics and responsibility in nanoengineering. Have you found this topic come up in classes or outside of classes?

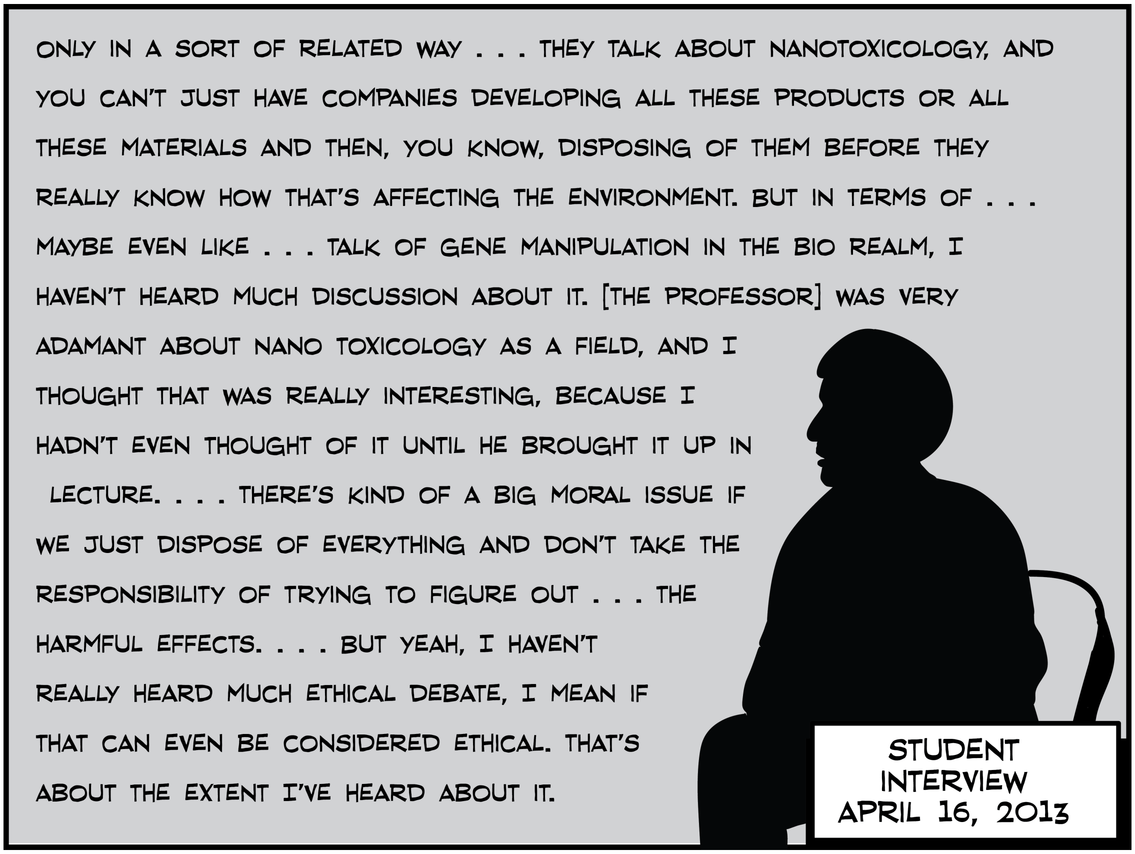

Illustration 73 Student interview, April 16, 2013. Student: "Only in a sort of related way..."

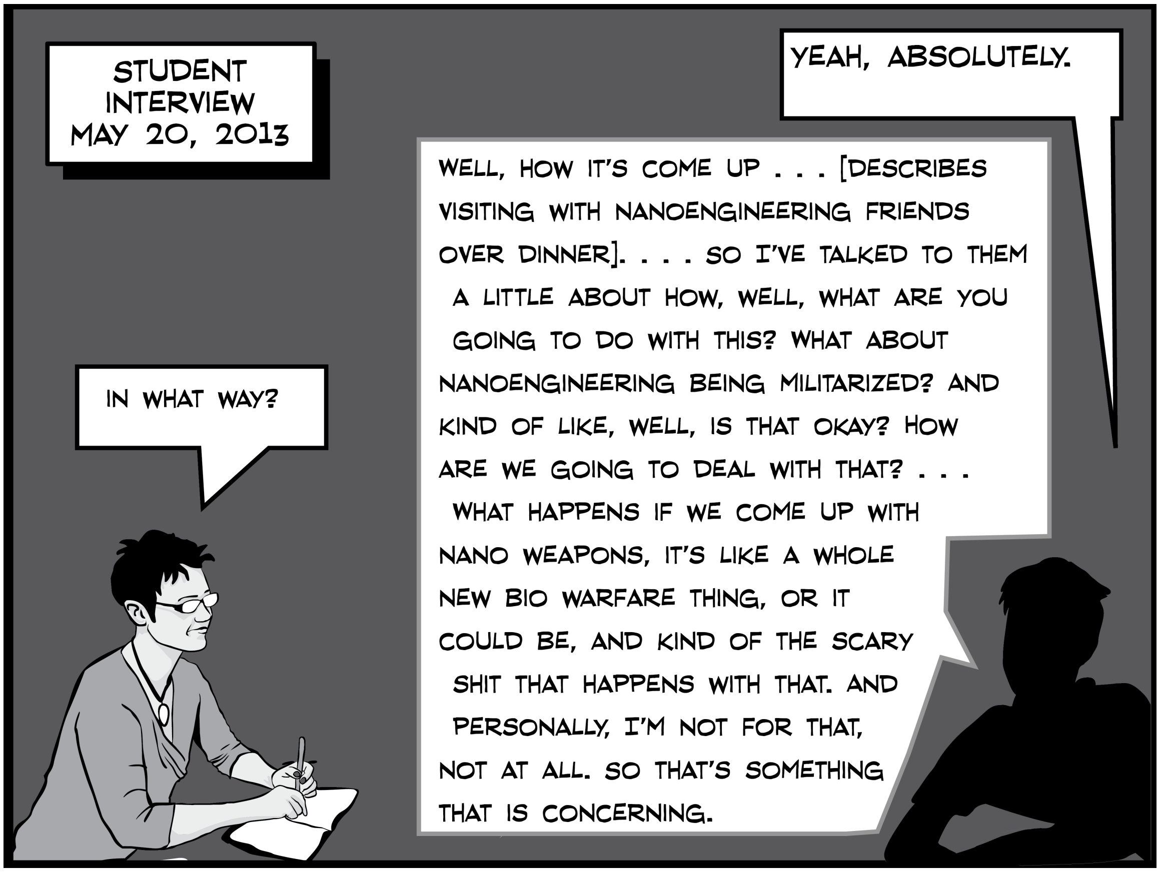

Illustration 74 Student interview, May 20, 2013. For this student, questions of ethics have come up in conversation with his friends outside of class.

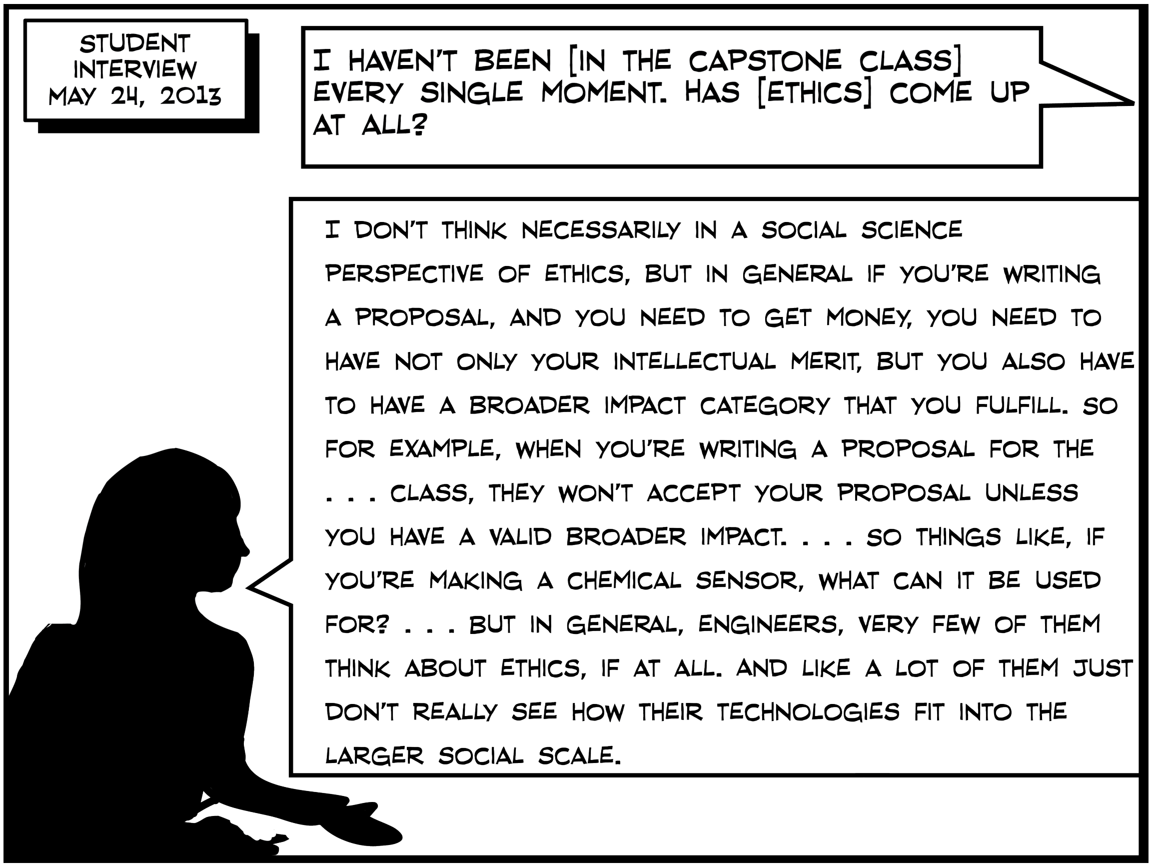

Illustration 75 Student interview, May 24, 2013. This student suggests that engineers' ability to traverse scale does not apply to the "social scale."

These lectures and homework problems reproduce a locus of interrelations between the technical, political, cultural, and moral. Bakhtin's concepts of heteroglossia and dialogism are compatible with feminist theories of epistemology and ontology—for example, Helen Longino's work, which challenges the "ideal of value neutrality" by considering knowledge production as an embodied social practice,[49] or Donna Haraway's articulation of situated knowledges as located in embodied subjects and partial

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49. Longino, *Science as Social Knowledge*, 13.

perspectives.[50] *Smaller is better* is a heteroglot phrase, containing traces of a broader set of discourses and the social worlds from which it emerges. It produces a particular worldview grounded in the partial perspectives of nanoengineers working within a particular part of the world and within a particular political economy. It answers the question “why nano?”—a question both asked and answered within logics of universality and progress.

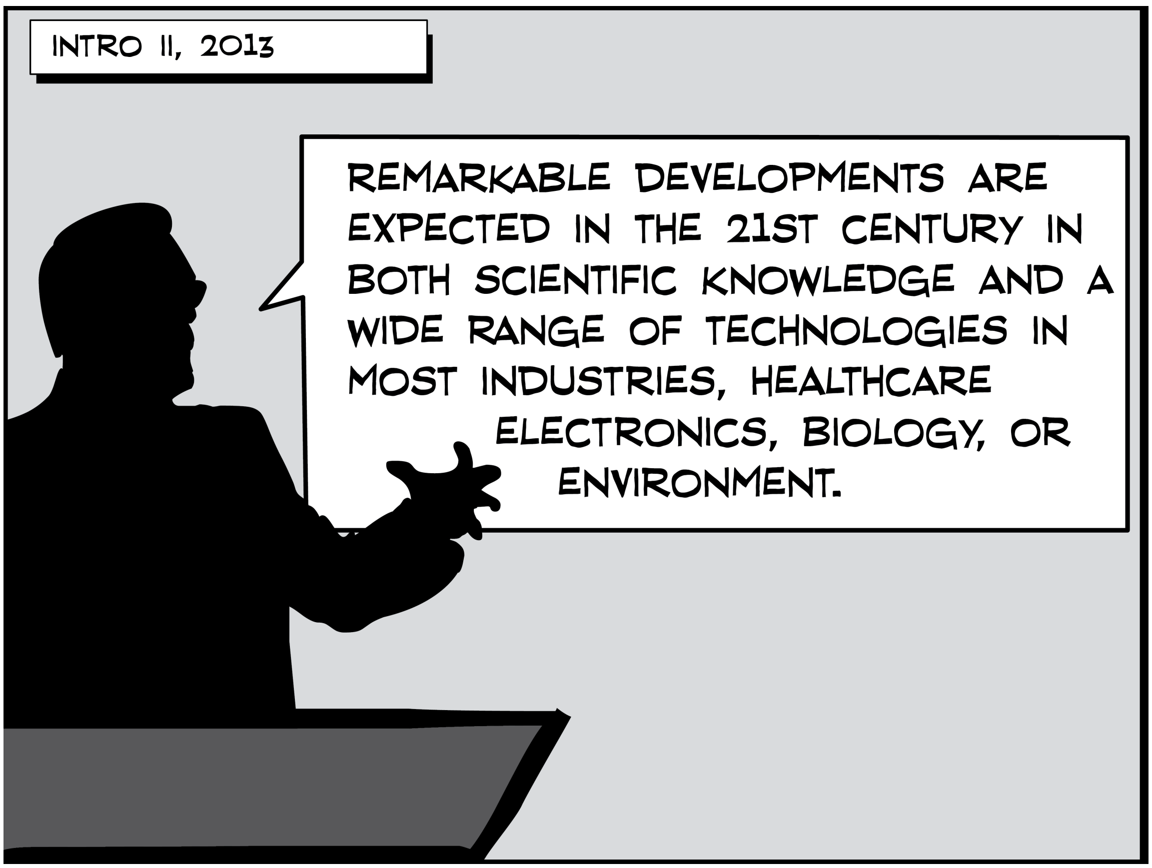

Illustration 76 Remarkable developments.

This worldview understands technoscientific progress in deterministic linearity, implicitly imagining a universal view of progress, of the future, and of who and what

50. Donna Haraway, "Situated Knowledges: The Science Question in Feminism and the Privilege of Partial Perspective," *Feminist Studies* 14, no. 3 (1988): 575-99.

counts within the phrase "the benefit of society." With research that promises to provide vastly improved treatments for cancer to those who can afford them, as well as long-lasting batteries and improved solar panels that could enable affordable alternatives to fossil fuels, I accept that specific benefits to specific beneficiaries are reasonable expectations of current nanotechnology-related research. What I wish to suggest, however, is that a pluralistic standpoint that embraces multiplicity when approaching assumptions about "progress," "the future," "mankind," and "benefit," can make room for the possibility that neither the in/visible nano world nor the in/visible future macro worlds that nanoengineers are attempting to create are inevitably better for all human and nonhuman inhabitants of these worlds. There is plenty of room at the bottom for this possibility as well. While many nanoengineers—and particularly nanotechnology companies—may have the economic and political power to realize their visions of the future, these futures may entail complicated socio-political and environmental dimensions that may not be fully addressed through the market.

While specific strategies for democratic mechanisms of addressing these issues are beyond the scope of this chapter, I want to outline a pedagogical strategy inspired by Barad's agential literacy for creating a more reflexive practice that requires a slightly different orientation to the small.[51] Incidentally, a reflexive engagement with who and what may or may not benefit from specific nanotechnologies can guide nanoengineers

51. See Barad "Reconceiving Scientific Literacy" for a detailed discussion of how agential literacy, extending her philosophy of agential realism, differs from scientific literacy.

toward producing futures that have broader societal validation and that are more sustainable while, at least in theory, also producing more success in market terms.[52]

Rather than *smaller is better*, I propose a shift in orientation that demands context, specificity, and an open-ended, democratic orientation to technoscientific production. For example, a question such as “When, how, and for whom might smaller be better?” could ground an introduction to scale and the scaling laws. The central principle of the identity, practice, and disciplinarity of nanoengineering need not hinge on the abstract principle that smaller *is* better. Rather, nanoengineering can locate itself as contributing expertise toward a particular kind of answer to the above question. This would ground the ethical responsibility of nanoengineers not only in realizing their “nano dreams”[53] for the benefit of society, but in providing specific kinds of technical expertise to partly answer the question, “When, how, and for whom might smaller be better?” While recognizing that technoscientific research and development is always accompanied by risk and uncertainty, the activity of imagining futures should visualize the myriad possibilities for downsides as robustly as for upsides in order to achieve benefit, and doing this requires

52. Charles Thorpe and Jane Gregory, "Producing the Post-Fordist Public: The Political Economy of Public Engagement with Science," *Science as Culture* 19, no. 3 (2010): 273-301. See Thorpe and Gregory for a critique of how “public engagement” as a mode of democratizing science can actually be a form of cooptation and control, preparing citizens to become consumers of technoscientific products. I revisit this in Chapter 5 in my discussion of the implications of training engineers as human capital.

53. The professor in this course frequently invokes the term “nano dream,” spelled as either one or two words, and concludes the class with an injunction to the students to follow their nano dreams. I have decided throughout this dissertation to spell it as two words, to suggest that they are dreams of nanotechnology rather than nanoscale dreams.

context, specificity, and a professional vision that can see—or at least imagine—what might lie outside any particular nano dream.[54]

While some students I interviewed expressed engaged and complicated relationships to questions of ethics, as suggested by the interview quotations opening this section, the students who did so were often drawing from outside the curriculum—citing

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54. H. Brune, Holger Ernst, Armin Grunwald, W. Grünwald, H. Hofmann, H. F. Krug, Peter Janich*, et al., Nanotechnology Assessment and Perspectives*, Berlin ; New York: Springer, 2006; Barbara Adam and Chris Groves, "Futures Tended: Care and Future-Oriented Responsibility," *Bulletin of Science, Technology & Society* 31, no. 1 (February 1, 2011): 17-27; Christopher Groves, "Horizons of Care: From Future Imaginaries to Responsible Research and Innovation," in *Shaping Emerging Technologies: Governance, Innovation, Discourse Studies of New and Emerging Technologies / S Net*, edited by Kornelia Konrad, Christopher Coenen, A. B. Dijkstra, Colin Milburn, Harro van Lente and Society for the Study of Nanoscience and Emerging Technologies (Berlin, Germany: AKA IOS Press, 2013); Richard Owen, Jack Stilgoe, Phil Macnaghten, Mike Gorman, Erik Fisher, and David Guston, "A Framework for Responsible Innovation," Chap. 2 in *Responsible Innovation: Managing the Responsible Emergence of Science and Innovation in Society*, edited by Richard Owen, J. R. Bessant and Maggy Heintz (West Sussex: John Wiley & Sons Inc., 2013); David Guston, "'Daddy, Can I Have a Puddle Gator?': Creativity, Anticipation, and Responsible Innovation," Chap. 6 in *Responsible Innovation: Managing the Responsible Emergence of Science and Innovation in Society*, edited by Richard Owen, J. R. Bessant and Maggy Heintz (West Sussex: John Wiley & Sons Inc., 2013), 109-42; Arie Rip, "Nanoscience and Nanotechnologies: Bridging Gaps through Constructive Technology Assessment," Chap. 9 in *Handbook of Transdisciplinary Research*, edited by Gertrude Hirsch Hadorn, Holger Hoffmann-Riem, Susette Biber-Klemm, Walter Grossenbacher-Mansuy, Dominique Joye, Christian Pohl, Urs Wiesmann and Elisabeth Zemp, (Netherlands: Springer, 2008)145-57; Barad, *Meeting the Universe Halfway*.

This sentiment—variously articulated—is widespread in STS, Constructive Technology Assessment (CTA), and Responsible Research and Innovation (RRI). For example, see Brune et al. for a discussion of ethical vision assessment, particularly the recommendation "to not communicate futuristic visions without pointing to the 'meta-knowledge' about the visions: premises, presuppositions, values involved, uncertainties etc." (431).

See also Adam and Groves' analysis of care as a mode through which responsibility can be refigured around interdependence rather than autonomy. Through care in this sense, one might examine nano dreams from multiple perspectives. Additionally, Groves writes in "Horizons of Care" that a "political imaginary of care" would consider "not only what a given technology might contribute to the fulfillment of human needs, but how it will affect the agency and identify of its users" (199).

See Owen et al. for an examination of responsible innovation as entailing engagement that is "anticipatory, reflective, inclusively deliberate, and responsive" (29), and Guston's further examination of anticipation and the politics of novelty.

See Arie Rip for a discussion of CTA and reflexivity.

See Barad's discussion, building on the work of Judith Butler, of constitutive exclusions in relation to responsibility in science.

such sources as science fiction, nonprofit work, military training, and engagement with the environment, as informing their sense of the potential moral dimensions of nano. Moreover, they expressed this even during my first interview with them in their first year of the program, indicating it was something they came in with. Yet these responses suggest that students may be receptive to and even welcome more robust engagement with ethics in the curriculum.

Orientating an introduction to scale and the scaling laws around a more open-ended notion of benefit that is grounded in context and specificity would generate different lecture slides, different scale-conversion problems, and potentially a different understanding of nanoengineering. Recall that these lectures began with an introduction to scale that compared nanoparticles to viruses, ants, and houses, representing the nanoscale as both ordinary and extraordinary. My critique, however, is not about whether any particular object can inhabit both the ordinary and the extraordinary simultaneously. Rather, it is about the way in which *smaller is better* tends to align the extraordinary with nano's promises and the ordinary with nano's presumed benign nature. Rejecting universalism and embracing a more reflexive engagement with the implications of going smaller would still allow for promissory visioning, but would demand that it be coupled with robust visioning of what lies outside such promises.

From this perspective, the professor could introduce students to scale by selecting objects for comparison specifically to raise questions rather than just communicate size. In selecting these objects and in engaging comparisons, rather than treating these scales of matter as ontologically discrete spaces—suggested by the term "world"—the lecture could emphasize the ways in which multiple scales are intra-actively co-producing each other.[55] For example, tobacco smoke has particles as small as 10 nanometers.[56]

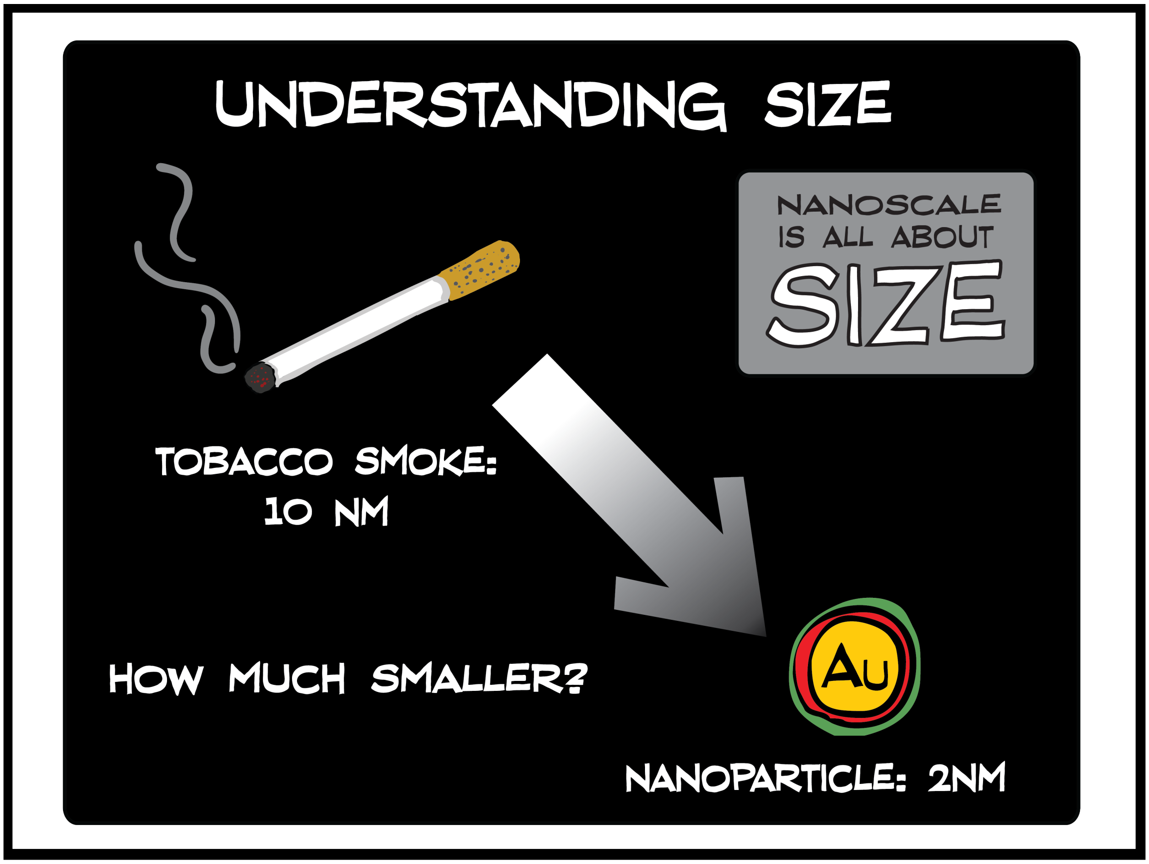

Illustration 77 Imagining a lecture slide that introduces scale with objects that raise questions.

A whole range of comparisons could be made that stay with tobacco to illustrate scale, not all of which need to be measurable in metric units: tobacco smoke, pesticides used on tobacco plants, cancer cells in humans, the diameter of a cigarette filter and the length of a typical cigarette, but also tobacco workers, tobacco farms and factories, tobacco

55. Barad, *Meeting the Universe Halfway.*

56. S.K. Sahu, M. Tiwari, R.C. Bhangare, and G.G. Pandit, "Particle Size Distribution of Mainstream and Exhaled Cigarette Smoke and Predictive Deposition in Human Respiratory Tract," *Aerosol and Air Quality Research* 13 (2013): 324-32.

regulatory regimes, tobacco advertising, the environmental impacts of cigarette filters, and so forth. The lecture could additionally engage nanoscale targeted drug delivery to cancer cells, an area of research important to this department. The professor could raise questions about whether such nano-based therapies for cancer would be expensive or available to everyone, and whether they would solve the problems of tobacco. This same principle applies to scale-conversion problems. Objects could be selected not just for their familiarity but also for the questions they may raise, such as nanoscale barcodes as tracking technologies.

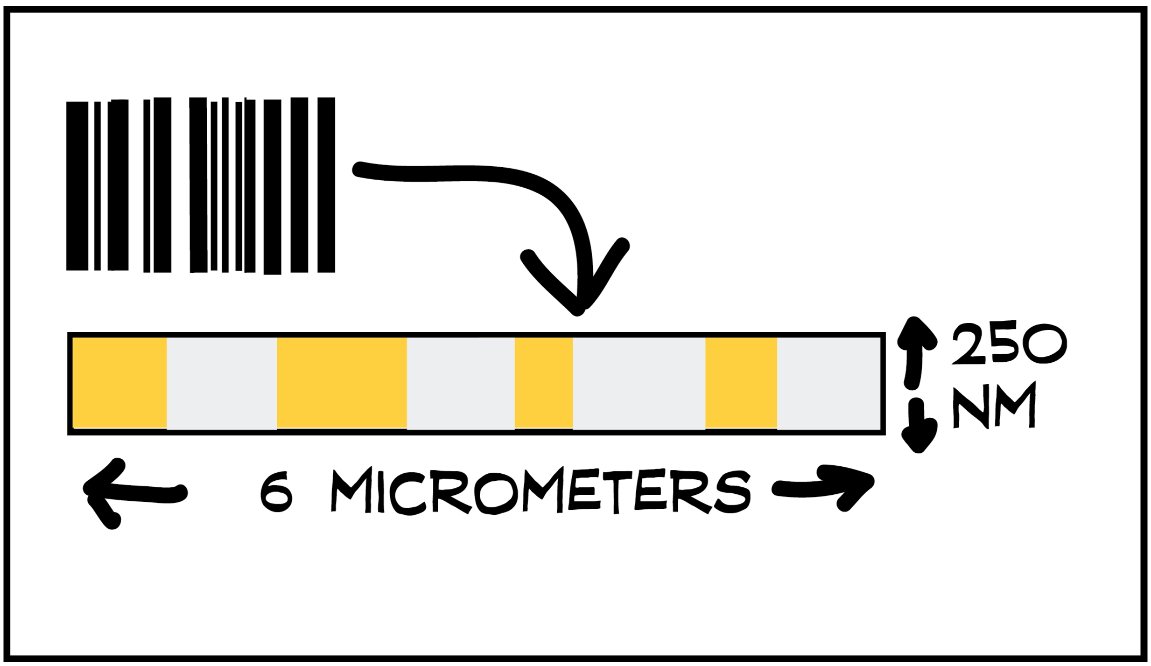

Illustration 78 Nanoscale barcode.

Objects can be selected to maximize the students' understanding of scale traversals, not only between metric units but also between their own research and its broader societal and environmental dimensions. This approach refigures scale as fluid and dynamic, with macro and nano always in mutual co-production. And it emphasizes that for nanoengineers to be successful, they have to consider these broader dimensions. Being able to traverse between nano, micro, and macro is not just a question of converting metric units.

The pictures of the baby and weightlifter, as well as the phrases “go nano: better strength-to-weight” and “changes/improvements,” could be eliminated. Instead, strength-to-weight ratio could be defined in relation to two or more nanotechnology applications, again specifically selected to invite conversation about their broader implications. For example, nanocellulose promises to be extremely strong, carbon neutral, and biodegradable. Researchers, such as Emily Cranston at McMaster University in Canada, are working to develop nanocellulose materials that can replace non-renewable materials.[57] Such nanocellulose materials could be incorporated into a range of products from food to biomedical sensors to military protective gear. Another example is carbon nanotubes, already widely in use, which are proving to have potential health impacts on workers. According to the CDC, carbon nanotubes (CNTs) can exhibit similar behaviors as asbestos in lung cells. Exposure to CNTs has caused adverse cardiovascular responses in mice and pulmonary inflammation in other laboratory animals.[58] Discussing nanocellulose and carbon nanotubes in the context of strength-to-weight ratios at the nanoscale teaches the technical aspects while also presenting a range of possible impacts.

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57. Emily Cranston, "Nanocellulose," McMaster University Industry Liaison Office, accessed September 25, 2014, http://milo.mcmaster.ca/portal/collaborate/nanocellulose-1/nanocellulose-sheet.

58. Centers for Disease Control and Prevention, “CDC Workplace Safety & Health Topics Nanotechnology FAQ,” accessed September 25, 2014, http://www.cdc.gov/niosh/topics/nanotech/faq.html.

Likewise, instead of presenting functional density as an inherent benefit, students could be asked to imagine scenarios for themselves or others in which more functions in a particular device might not constitute a benefit. They could be asked whether there might be an upper limit to the number of desirable functions in a device, and what would constitute such an upper limit. What problems might come with the all-in-one device?

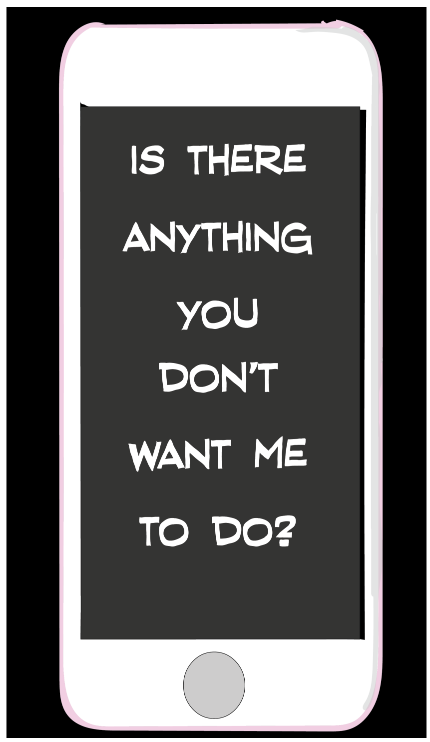

Illustration 79 Limits of functional density.

The benefits and drawbacks of functional density may depend on the specific device, the user, the usage context, and the nature of the evaluation. This kind of engagement enacts a reflexive practice that remains open to the possibility that smaller might not be better. It addresses not only moral responsibility but also commercial sensibility: devices with a functional density that is perceived as burdensome may actually fail in the marketplace.

Conclusion

Innovation regimes are driven by promissory discourse[59] and a technofix mentality that brackets uncertainties for risk materializations.[60] Yet in cultivating the professional identity of nanoengineering, the UC San Diego Department of NanoEngineering and its undergraduate major present opportunities for embracing a more complex relationship to heterogeneous spatial and temporal practices of world-making. Already positioned as foregrounding scale, backgrounding disciplinary boundaries, and genuinely desiring to improve the world in many domains, including health and the environment, nanoengineering would benefit from taking its own rhetoric as materially significant rather than as “merely” rhetoric. That is, scale does matter. Humans and nonhumans are not only traversing scale all the time, they are also worlding at different scales: how can nanoengineers help us to think about the ways this can happen? Futures matter, and the ways people imagine the future and endeavor to make the future matter: how can nanoengineers be part of a broader dialog about the multiplicity of worldviews, with their attendant hopes and fears, that inform these imaginings?[61] Nanoengineers can position themselves as having crucial expertise to contribute to democratic processes of determining who and what may or may not benefit from nanoscale manipulations of matter. But the questions and the answers demand

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59. Kaushik Sunder Rajan, *Biocapital: The Constitution of Postgenomic Life*, Durham: Duke University Press, 2006.

60. Barbara Adam, and Chris Groves, *Future Matters: Action, Knowledge, Ethics*, Supplements to the Study of Time, Leiden ; Boston: Brill, 2007.

61 Rosalyn W. Berne, *Nanotalk: Conversations with Scientists and Engineers About Ethics, Meaning, and Belief in the Development of Nanotechnology*, Mahwah, NJ: Lawrence Erlbaum, 2006.

specificity and context in order to guide nanoengineering toward its goal of producing beneficial technologies.

Chapter 3 extends and elaborates on material that appears in “Smaller is Better? Learning an Ethos and Worldview in Nanoengineering Education,” *NanoEthics*, August 2015, Volume 9, Issue 2, pp 109-122. The dissertation author was the primary investigator and author of this paper.

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Chapter 4 Self-Assembly and the Invisible Hand: Producing the Autonomous Individuals of a Discipline

Introduction

In chapters 2 and 3, I focused on the undergraduate nanoengineering curriculum as I examined how the higher-ed science classroom works as a central site for the ethics and politics of knowledge production. By analyzing the undergraduate curriculum—a key component of this disciplinary formation—I showed how popular culture is enrolled in producing an ethos and identity for the nanoengineer, as well as how the curriculum itself constitutes a set of technocultural practices. I further showed how these technocultural practices incorporate assumptions about nature and man, science and progress, and the good, while simultaneously producing a worldview that positions the nanoengineer as an intrinsically ethical actor who benefits society through nanotechnologically-enabled progress. In this chapter, I will continue to examine technocultural practices that incorporate such assumptions, and that implicitly reflect a particular worldview. But rather than focusing on the curriculum per se, I move into the laboratory as I explore the relationships between the material and discursive practices of self-assembly—a category of nanofabrication techniques—and particular ideologies of markets, nature, and governance. I'm especially interested in the repeated emphasis that no hand—either human or robot—manipulates this assembly.[1] The laboratory that I observed on a weekly basis for one-and-a-half years was primarily focused on researching self-assembly, with

1. George Whitesides, G.M., J.K. Kriebel, and B.T. Mayers, "Self-Assembly and Nanostructured Materials," in *Nanoscale Assembly: Chemical Techniques* edited by W.T.S. Huck, Springer (formerly Kluwer), 2005. This emphasis is widespread in discussions of self-assembly, but I cite George Whitesides, an early promoter and adopter of self-assembly, who emphasizes it often and in print.

an interest in using self-assembly synthesis of nanostructures to create novel solar cell technologies.

Having primarily shadowed a couple of undergraduate students in the laboratory who participated in experiments that developed these techniques, I regard the laboratory as another site of pedagogy (and in this sense, isn't entirely separate from the curriculum), and a site that is key for understanding not only knowledge production but also disciplinary formation. Therefore my examination of self-assembly focuses on the constitution of two "selves" that are both central to the discipline: the self of the nanoparticle and simultaneously that of the nanoengineer. I argue that the predominant view of self-assembly, which is that it is something that occurs on all scales—from cellular reproduction to galaxy formation—is also implicitly at work in assumptions about the formation of the nanoengineer and of the discipline. That is, nanoparticles are not the only individuals self-assembling; human individuals are also expected to autonomously assemble into the larger functional structures of the department, the university, the discipline, and ultimately the innovation economy within which they will labor.

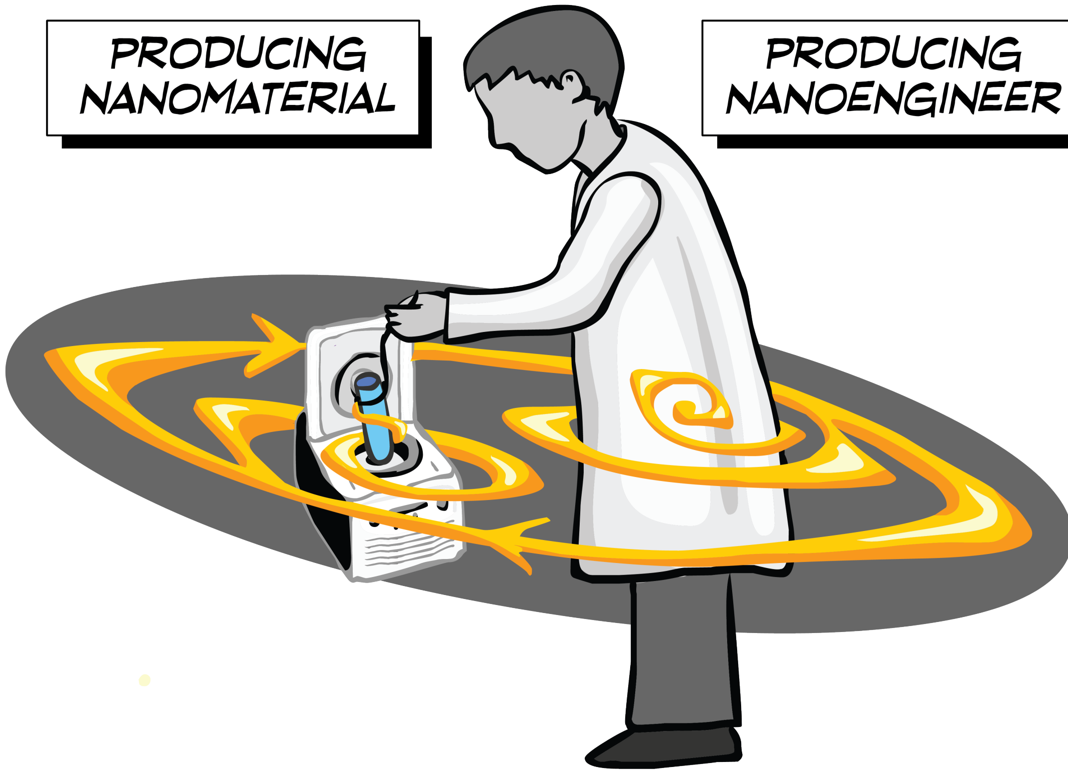

Illustration 80 Producing nanomaterial, producing nanoengineer.

Self-assembly generally refers to a range of practices that involve producing specific conditions such that a set of elements will form functional structures in a predictable way. It is somewhat analogous to putting a bunch of elements in a solution into a jar, shaking it up, and having those elements form crystals—though it's more complicated than that, and there are different techniques for achieving self-assembly. It is considered "bottom up" and is contrasted with so-called "top down" mechanisms that would individually place each element into the structure.

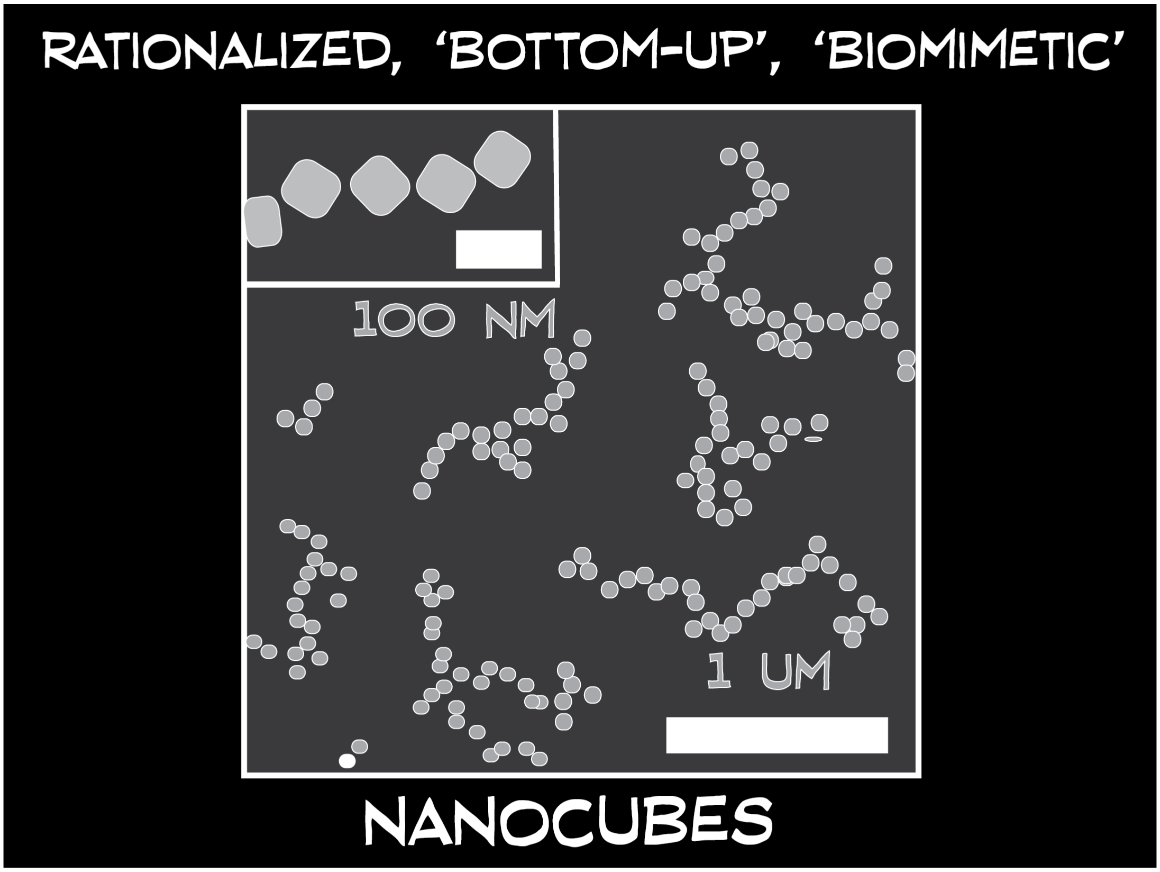

Illustration 81 Rationalized, bottom-up, biomimetic nanocubes.

In my site it is understood as the rationalized bottom-up and biomimetic organization of individuals (particles) into hierarchical, functional structures. I argue that the emphasis on the self that needs no hand elides the structures of top-down control that enable and constrain these individuals to act in predictable ways. Drawing on Philip Mirowski's analysis of neoliberal notions of the market as nature's ideal information processor,[2] I consider the ways in which the individuals of self-assembly are further understood as informational units enacting a bottom-up self-organization analogous to the behaviors of

2. Philip Mirowski, *Science-Mart : Privatizing American Science*, Cambridge, Mass.: Harvard University Press, 2011, 196.

rational actors in the formation of markets. Indeed, the rhetoric of no hand in self-assembly strongly resembles that of an invisible hand in Adam Smith's economics. At the same time, the active efforts necessary for creating the conditions that enable these autonomous units to assemble recall neoliberal theory's shift from classical economics—the shift from a naturalized to a constructed market[3] in which the state actively creates and maintains the conditions that enable capitalist competition.

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3. Wendy Brown, *Undoing the Demos : Neoliberalism's Stealth Revolution*, First Edition, ed. New York Cambridge, Massachusetts: Zone Books MIT Press, 2015. Brown is not the only person to talk about this distinction between neoliberalism and classical economics, but in my use of the particular phrasing of constructivism I am drawing from her. Whereas classical economics posited a natural market that needed no active creation or maintenance, neoliberalism treats the market as natural but espouses an active state role in creating and maintaining it.

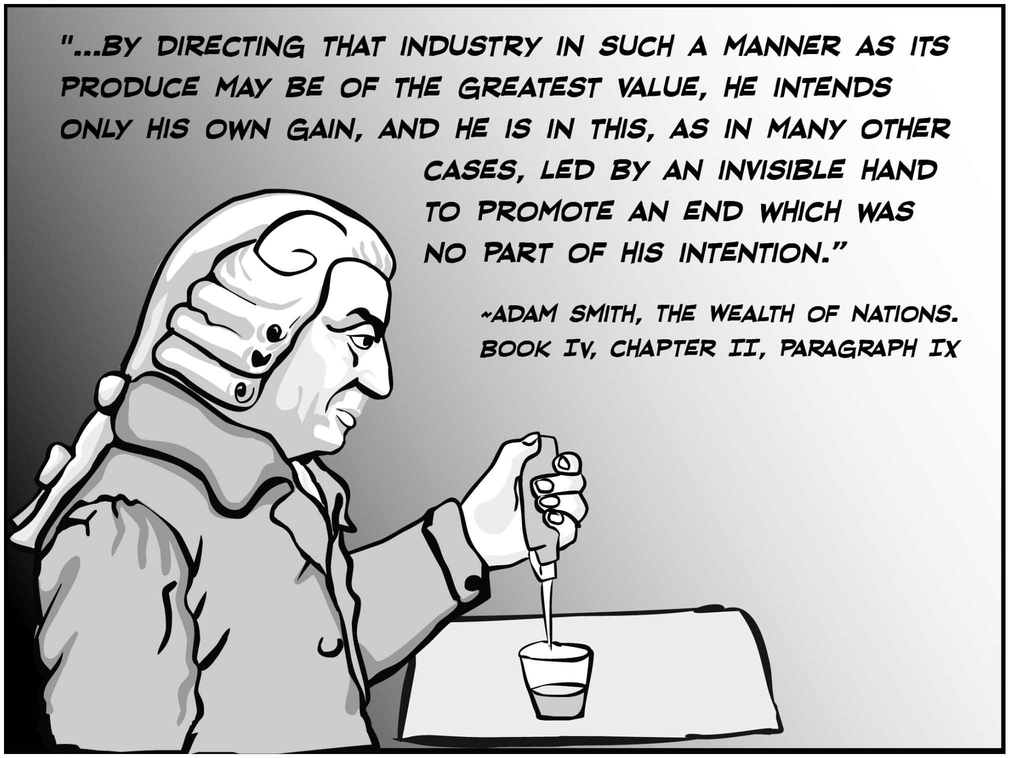

Illustration 82 Adam Smith. "…By directing that industry in such a manner as its produce may be of the greatest value, he intends only his own gain, and he is in this, as in many other cases, led by an invisible hand to promote an end which was no part of his intention."[4]

It is this resemblance between no hand and an invisible hand that led me to consider self-assembly as potentially having relevance beyond the nanoparticle individuals that it explicitly references, to shed light as well on the logics that govern nanoengineering students.

A Brief History of Self-Assembly

An online search for the term "self-assembly" suggests that it begins to appear in biological studies of the cell in the 1950s, in organic and then inorganic chemistry in the 1970s and 80s, and then in relation to nanotechnology in the late 1980s to early 1990s.

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4. Adam Smith and Edwin Cannan, *An Inquiry into the Nature and Causes of the Wealth of Nations*. 2 vols London,: Methuen & co., 1904, Par. IV.2.9.

For example, a 1955 article in *American Scientist* draws on information theory to discuss cell reproduction, using the metaphors of a printing process and self-assembly. Referring to chromosomes, Homer Jacobson writes:

> Their complexity and known hereditary function in the higher organisms, make it seem as though they are the *plans* produced in the first step discussed above, by a simple "printing" process. The cytoplasm, less striking under biological stain reagents, may accomplish the real duplication, that is, the self-assembly of the second step.[5]

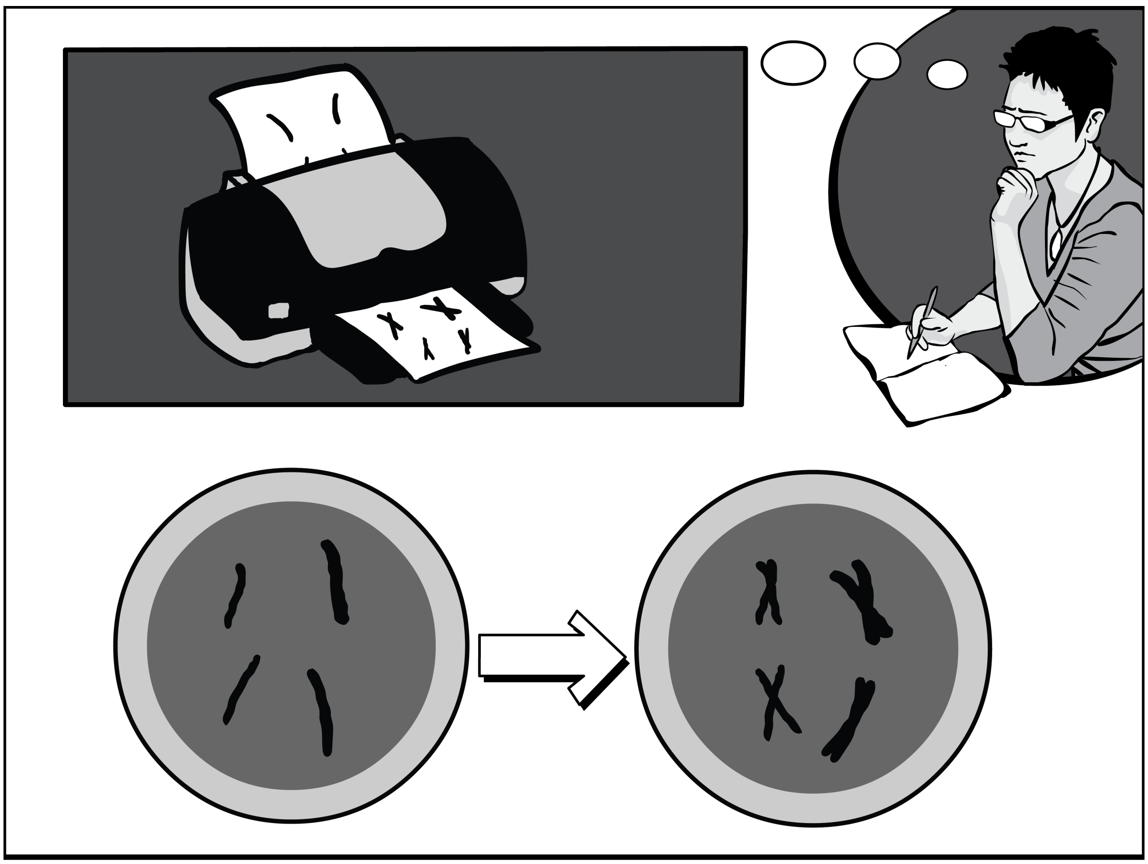

Illustration 83 Cell reproduction as a printing process.

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5. Homer Jacobson, "Information, Reproduction and the Origin of Life," *American Scientist* 43, no. 1 (January 1955): 120, emphasis original. Note that in 2007 Jacobson redacted this article in part because it was frequently cited by creationists as support of anti-evolution views (http://www.nytimes.com/2007/10/25/science/25jacobson.html?_r=0, accessed December 12, 2015).

Here, the chromosomes are understood in terms of information mechanisms that have codes, or plans, which are printed. The duplication is described in terms of self-assembly, the mechanism in which a copy is produced based on these plans. Jacobson goes on to say that:

> Life, then, is a temporary reversal of a universal trend by means of the production of information mechanisms. Living beings reproduce, cerebrate, order their environment into cities, nuclear bombs, and scientific publications, and even build engines to trap some of the useful energy of the degrading solar photons. All of these processes have in common the production of information. This minor reversal of entropy gain is probably an accident in the history of the universe…. [It] presumably happened at some early time, or times, corresponding to the first coalescence of matter into a self-reproducing structure which could extract energy from the environment for its first self-assembly.[6]

Jacobson's extrapolation toward ever-larger structures—cities, bombs, human networks of communication, etc.—is echoed in later descriptions of self-assembly, which I will return to. Here, importantly, self-assembly is articulated in terms of the self-reproduction of structures in nature, a process that is central to life itself and which entails a form of reproduction that executes according to information coded in the "self" and which draws on energy from the environment.

In *Scientific American*—a magazine with a reputation, particularly historically, for identifying emerging trends and publishing articles predominantly written by scientists[7]—the term "self-assembly" continues to appear in articles in the 1960s and 1970s. As a mechanical metaphor used to describe the biological reproduction of cellular

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6. Ibid., 121.

7. http://www.scientificamerican.com/page/about-scientific-american/, accessed December 11, 2015.

structures, it is often mixed with metaphors of printing and coding, and the transcriptional work of DNA and RNA. Assembly appears primarily reserved for the building and production of new structures based on information that is self-contained within the biological structures engaged in this self-reproduction. For example, a 1966 article titled "The Genetic Control of the Shape of a Virus" has the subtitle: "The protein shell of a virus is an assembly of subunits."[8] Another article in 1967 titled "Building a Bacterial Virus" examines what the maximum level of complexity is before "self-assembly becomes inadequate to the task of directing the building process" of biological parts.[9] It is "self"-assembly because the information directing the assembly is contained within the units themselves. Yet it is understood that in terms of biological reproduction, there is an upper threshold of complexity beyond which self-assembly no longer directs the building process, or assembly, of larger structures.

By the 1970s and 80s, chemists invoke this same language of assembly in descriptions of research on the chemical synthesis of organic and inorganic molecules. George Whitesides, a prominent chemist at Harvard, is a key figure in researching self-assembly in chemical synthesis, and by the late 1980s and early 90s he begins to discuss self-assembly in relation to nanotechnology. An article he publishes in *Scientific American* in 1995, called "Self-Assembling Materials," links the self-assembly of cellular

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8. Edouard, Kellenberger, "The Genetic Control of the Shape of a Virus," *Scientific American* 215, no. 6 (December 1966): 32-9.

9. William B. Wood, and R. S. Edgar, "Building a Bacterial Virus," *Scientific American* 217, no. 1 (July 1967): 61.

structures to the self-assembly of nanomaterials.[10] The article is worth a close examination because he explicitly links cellular reproduction in nature with the potential for using self-assembly to build mechanical machinery. The subtitle of the article reflects this: “The smaller, more complex machines of the future cannot be built with current methods: they must almost make themselves.”[11] He defines self-assembly as a “manufacturing strategy based on machines and materials that virtually make themselves,” and says that:

> A self-assembling process is one in which humans are *not* actively involved, in which atoms, molecules, aggregates of molecules and components arrange themselves into ordered, functioning entities without human intervention…. Self-assembly omits the human hand from the building. People may design the process, and they may launch it, but once under way it proceeds according to its own internal plan, either toward an energetically stable form or toward some system whose form and function are encoded in its parts.[12]

Note that his list of the types of elements that self-assemble abstracts from atoms and molecules to “components,” and his description refers to building that occurs according to plans encoded in these components. This is language that is strikingly similar to Homer Jacobson’s 1955 description of cellular reproduction. In fact, following this definition of self-assembly, Whitesides goes on to explain that self-assembly is “inspired by nature,” citing a living cell and a raindrop as examples of natural entities arising “from

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10. George Whitesides, "Self-Assembling Materials," *Scientific American* 273 (September 1995): 146-49.

11. Ibid., 146.

12. Ibid., 146, emphasis original.

physical principles or instructions implicit in their components."[13] Again, like Jacobson, Whitesides looks at multiples scales of nature in citing examples of self-assembly.

He then describes in more technical detail research on self-assembled monolayers (SAMs, which are one- to two-nanometer thick films) and buckytubes (electrical wires with nanometer-scale diameter). These are areas of research that are explicitly driven by visions of self-assembled machinery and the desire to control and manipulate matter on the nanoscale. Whitesides emphasizes that self-assembly occurs "without human intervention" and that it "omits the human hand."[14] Using the terms "component" and "molecule" interchangeably and emphasizing that they are informational units, he describes biology as "the pinnacle of functional self-assembly."[15] And in describing cell structures he writes that they are "self-assembled: no hand—robotic or human—places their components together."[16]

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13. Ibid., 146.

14. George M. Whitesides and Bartosz Grzybowski, "Self-Assembly at All Scales," *Science* 295, no. MAR 29 (2002): 2418.

15. Mila Boncheva, Derek A. Bruzewicz, and George M. Whitesides, "Millimeter-Scale Self-Assembly and Its Applications," *Pure Appl. Chem.* 75, no. 5 (2003): 628.

16. G.M. Whitesides, J.K. Kriebel, and B.T. Mayers, "Self-Assembly and Nanostructured Materials," In *Nanoscale Assembly: Chemical Techniques*, edited by W.T.S. Huck: Springer (formerly Kluwer), 2005, 220.

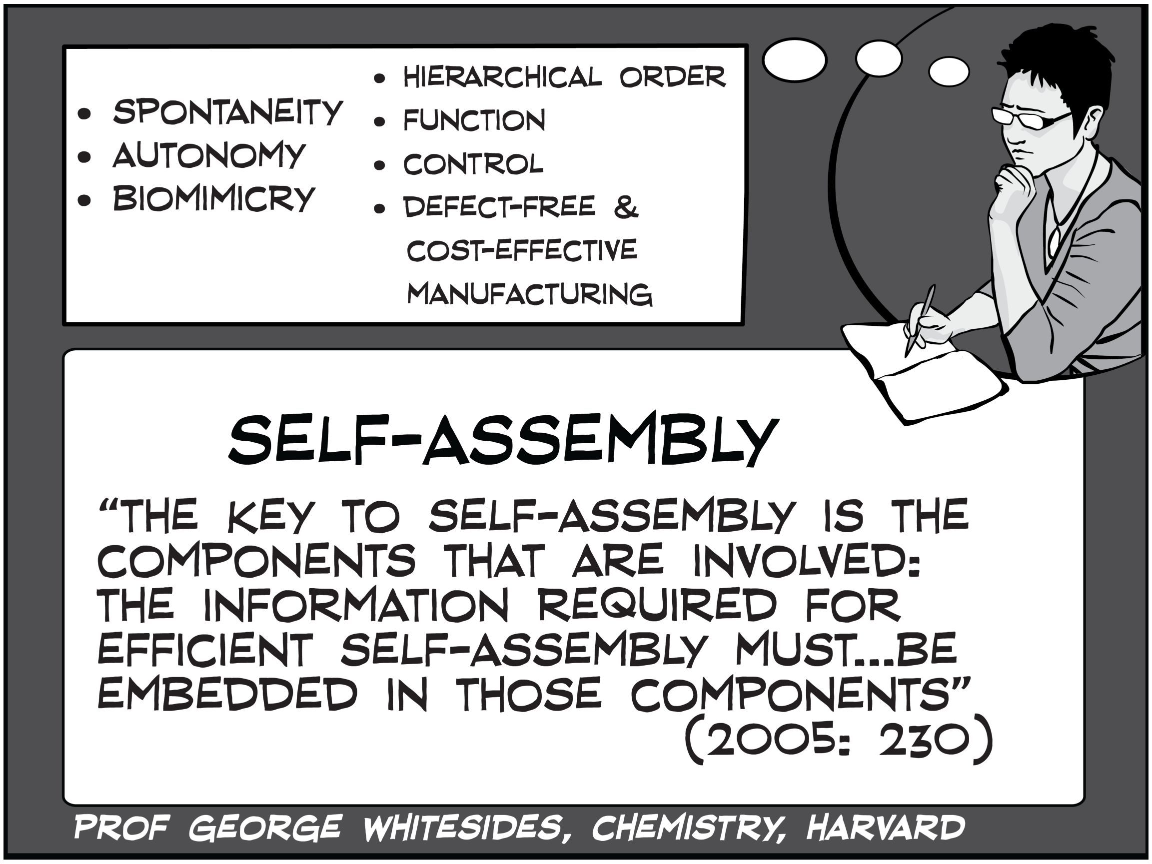

Illustration 84 Whitesides on self-assembly. "The key to self-assembly is the components that are involved: the information required for efficient self-assembly must…be embedded in those components."[17]

One of the primary self-assembly techniques used in the lab I'm observing and in the undergraduate laboratory class—called the Langmuir-Blodgett technique—was actually developed in the 1930s for generating films of larger molecules; it is not resignified as a "self-assembly" technique, so far as I can tell, until it is used to arrange "nanoscale building blocks."[18] Why does it become considered a technique of nanoscale synthesis that uses self-assembly, and why then?

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17. George Whitesides, J.K. Kriebel, and B.T. Mayers, "Self-Assembly and Nanostructured Materials," In *Nanoscale Assembly: Chemical Techniques*, edited by W.T.S. Huck: Springer (formerly Kluwer), 2005, 230.

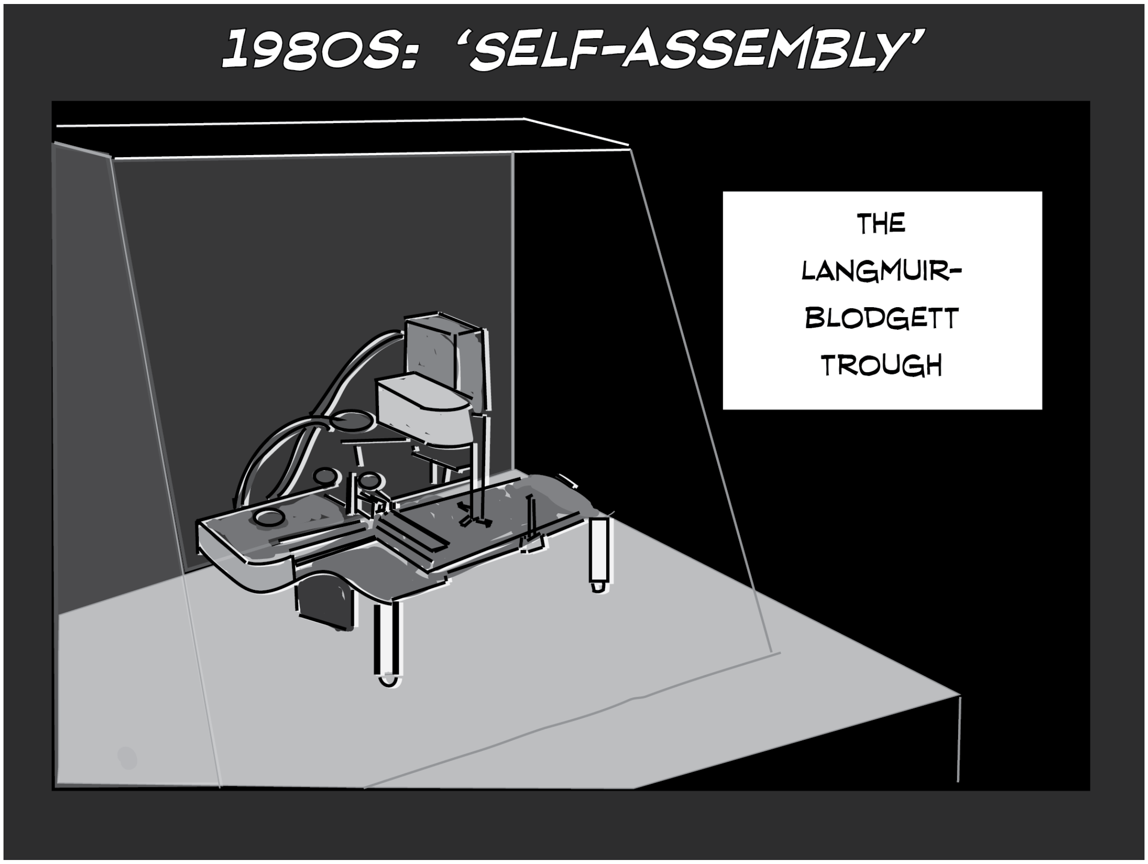

Illustration 85 Langmuir-Blodgett Trough.

The PI of the lab that I have observed previously worked with Whitesides and, in response to my inquiry, indicated she wasn't sure but speculated that the term "self-assembly" might have been coined by Whitesides.[19] As I've discussed, however, the term does precede Whitesides in descriptions of cell reproduction and cell membrane production in the 1950s and 60s. Yet Whitesides was certainly an early adopter and promoter of self-assembly in chemical syntheses of molecules, in SAM (self-assembled

18. Andrea Tao, Jiaxing Huang, Peidong Yang, "Langmuir-Blodgettry of Nanocrystals and Nanowires," *Accounts of Chemical Research*, 41, No. 12 (December 2008): 1665.

19. This occurred in an impromptu exchange while I was observing the laboratory capstone class, Spring 2014.

monolayer) research, and in using the Langmuir-Blodgett technique for synthesizing SAMs.

Around the same time that the Langmuir-Blodgett technique is incorporated into the discourses and practices of self-assembly, Eric Drexler publishes *Engines of Creation: The Coming Era of Nanotechnology* (1986). In it, he popularizes the promise of molecular machinery and the idea of a nanoscale universal assembler that would enable the placement of "atoms in almost any reasonable arrangement" and that would "let us build almost anything that the laws of nature allow to exist."[20]

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20. Eric Drexler, *Engines of Creation*. 1st ed. Garden City, N.Y.: Anchor Press/Doubleday, 1986m 14.

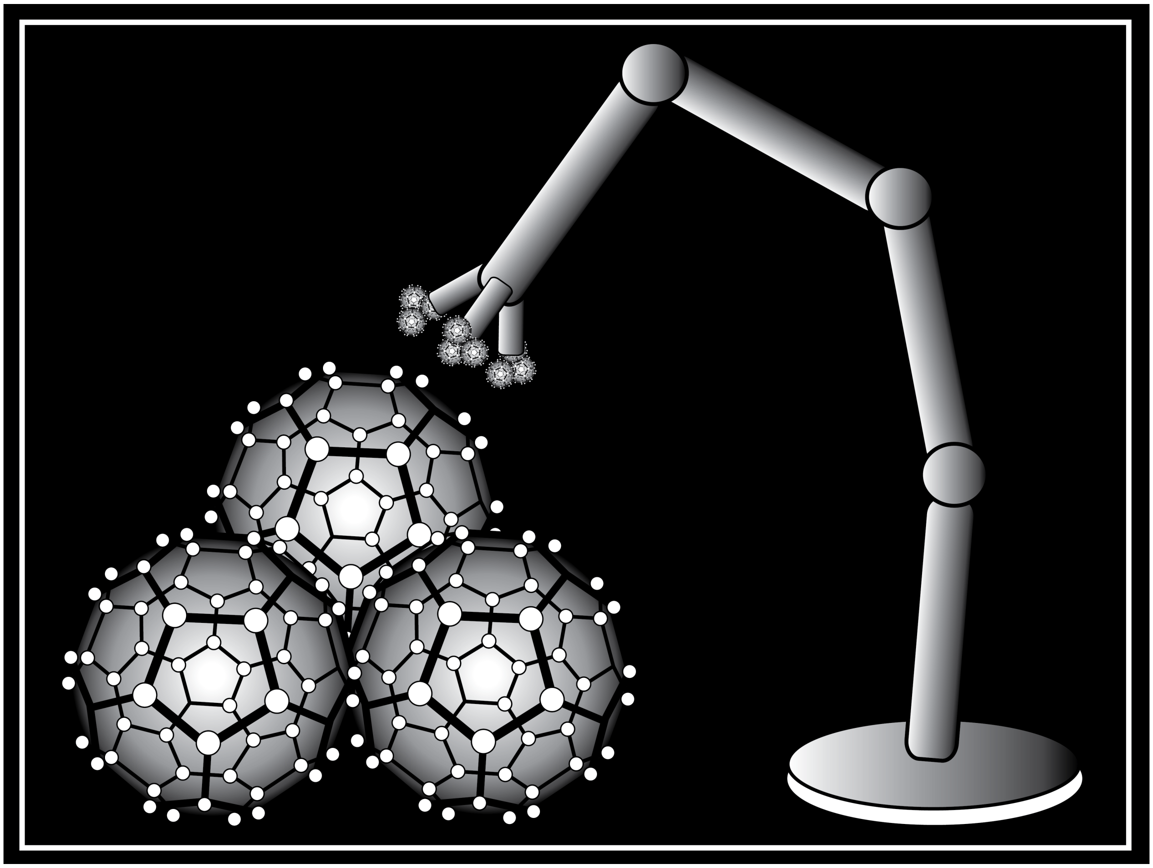

Illustration 86 Imagining molecular assembly.

Citing the self-assembling structures of the biological world, Drexler writes:

> Whether in cells or not, nanomachines obey the universal laws of nature. Ordinary chemical bonds hold their atoms together, and ordinary chemical reactions (guided by other nanomachines) assemble them."[21]

Dropping the "self" in his description of universal assemblers, Drexler nevertheless emphasizes that the inspiration for such nanomachinery is in the self-assembly of cellular reproduction, and that the information that would guide the assembler's actions would be encoded into the machinery.

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21. Ibid., 8-9.

In 2002 Whitesides defines self-assembly unambiguously as "the autonomous organization of components into patterns or structures without human intervention" which are "common throughout nature and technology" and he describes six reasons for interest in self-assembly:

> First, humans are attracted by the appearance of order from disorder. Second, living cells self-assemble, and understanding life will therefore require understanding self-assembly. The cell also offers countless examples of functional self-assembly that stimulate the design of non-living systems. Third, self-assembly is one of the few practical strategies for making ensembles of nanostructures. It will therefore be an essential part of nanotechnology. Fourth, manufacturing and robotics will benefit from applications of self-assembly. Fifth, self-assembly is common to many dynamic, multicomponent systems, from smart materials and self-healing structures to netted sensors and computer networks. Finally, the focus on spontaneous development of patterns bridges the study of distinct components and the study of systems with many interacting components. It thereby connects reductionism to complexity and emergence.[22]

This statement does a lot of work. Suggesting that self-assembly is a natural topic of human inquiry because of its centrality to biological life, it also positions self-assembly as key to nanotechnology, manufacturing, robotics, and dynamic systems. It is of interest on theoretical and practical levels, from understanding the foundations of life to engineering robots and networks. Self-assembly bridges science and engineering, and the study of the behavior of individual components with that of the behavior of systems. Importantly, in relation to nanotechnology, it traverses scale in the sense that self-assembly is taken to occur at all different scales. Previously I pointed out that in 1955 Homer Jacobson emphasized that the "production of information" and "reversal of entropy" were characteristic of all living systems, not only within the cell, but in the

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22. George M. Whitesides and Bartosz Grzybowski, "Self-Assembly at All Scales," *Science* 295, no. MAR 29 (2002): 2418.

production of cities and nuclear bombs. Similarly, in this 2002 article cited above by Whitesides and Grzybowski entitled "Self-Assembly at All Scales," self-assembly is identified as something that transcends scale: "They [self-assembling processes] involve components from the molecular (crystals) to the planetary (weather systems) scale."[23] A table listing examples of self-assembly includes swarms of ants and schools of fish, weather patterns, solar systems, and galaxies.[24]

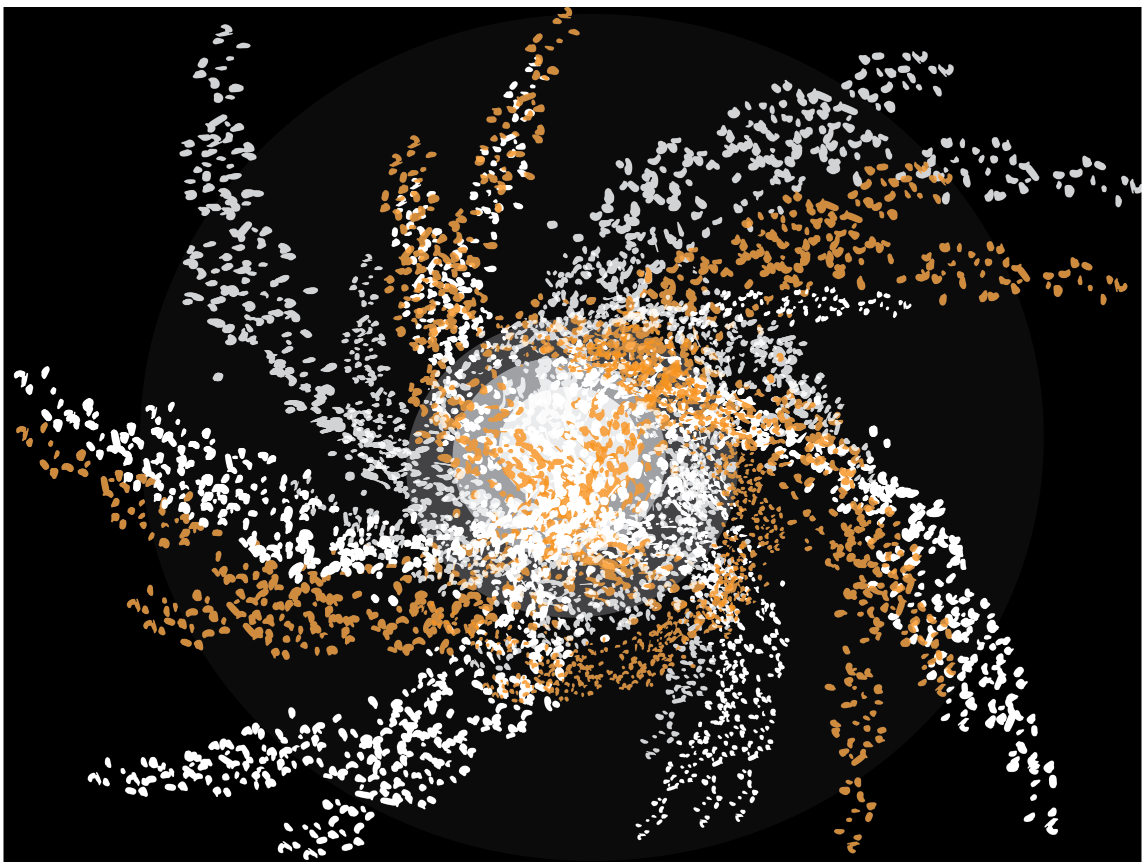

Illustration 87 Galaxy.

23. Ibid., 2418.

24. Ibid., 2419.

Self-assembly, like nanoengineering more broadly as I showed in Chapter 3, bridges different domains, disciplines, and scales. As synecdoche for nanoengineering, it is a biomimetic mode of controlling and manipulating the material world that defies traditional distinctions between the theoretical and the applied, or between different disciplines or scales. This is something I will return to in Chapter 6, where I discuss how the category of "translational research" comes to replace these distinctions.

So while the Langmuir-Blodgett technique existed well before biologists began to describe cellular reproduction in terms of self-assembly in the 1950s and 60s, by the late 1980s it comes to be understood as a self-assembly technique for producing SAMs (self-assembled monolayers, or nanometer-thick films). By the time this resignification occurs, biologists and chemists are routinely describing the biological world of cellular reproduction in terms of machinery; printing, coding, information, and transcription; and self-assembly. Chemists are actively attempting to mimic these processes of self-assembly in the lab. New instrumentation is also emerging that makes the atomic world visible for the first time, such as the invention of the scanning tunneling microscope in 1981. Nanotechnology is becoming popularized through Drexler's *Engines of Creation,* the discoveries of buckyballs and quantum dots in 1985, the invention of the atomic force microscope in 1986, and Don Eigler's and Erhard Schweizer's manipulation of 35 xenon atoms to spell out the IBM logo in 1989.[25] And self-assembly is coming to be seen as ubiquitous across all scales, a process in which components containing coded instructions execute on those instructions to build larger, ordered, functional structures.

25. http://www.nano.gov/timeline, accessed December 15, 2015.

It is not my intent to suggest a causal chain of events, or to present self-assembly as a self-evident or naturalized unfolding of events and scientific explanations. I am suggesting that by the 1980s self-assembly becomes a widely available explanatory trope for understanding the ways that functional structures might assemble or be assembled based on information self-contained within the subunits of a structure. As such, it is grounded in understandings of how life, and nature more generally, generates structures across scales, from microbiological life to galaxies.

Self-Assembly in the NanoEngineering Lab and Classroom

As I have indicated, in my site self-assembly is described as a technique of nanomanufacturing or nanosynthesis that is autonomous, bottom-up, and biomimetic. The PI of the lab I observed who does research on self-assembly for applications in bio- and optical sensors explained:

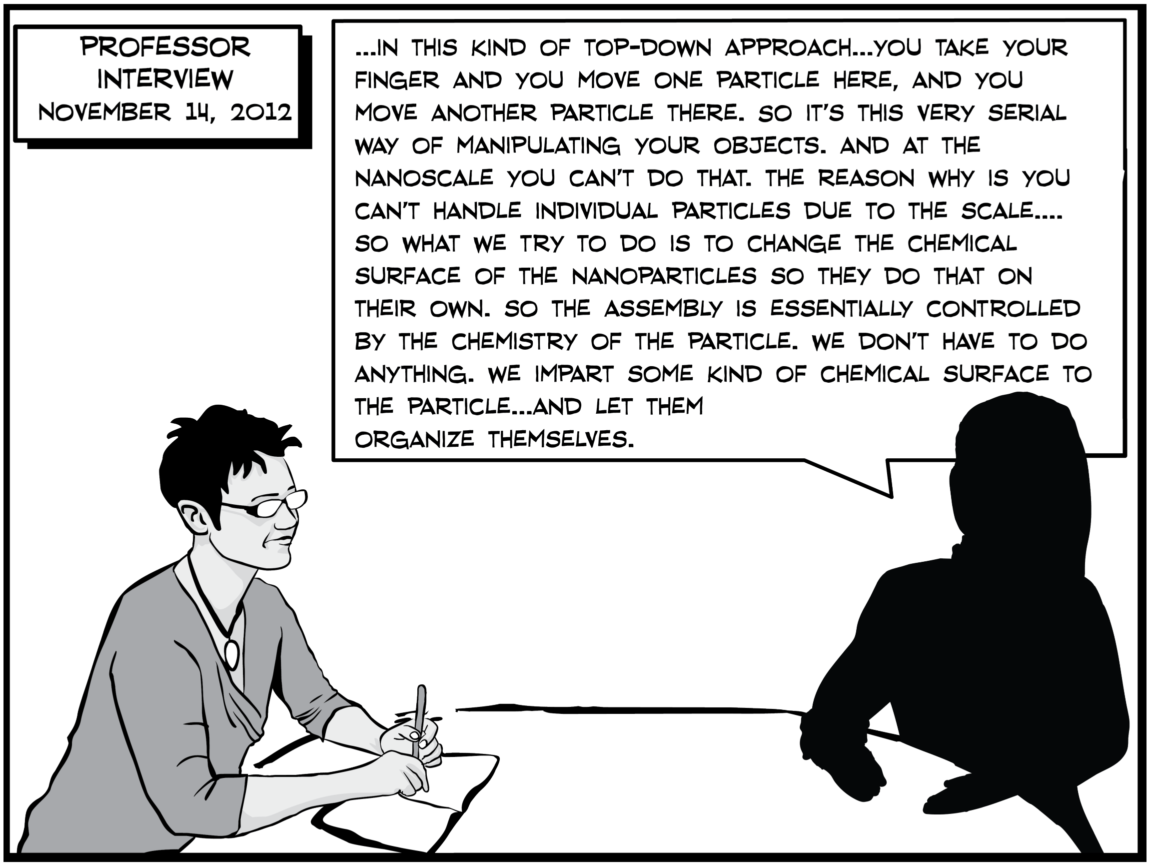

Illustration 88 Professor interview, top-down versus bottom-up. "In this kind of top-down approach...you take your finger and you move one particle here, and you move another particle there. So it's this very serial way of manipulating your objects. And at the nanoscale you can't do that. The reason why is you can't handle individual particles due to the scale.... So what we try to do is to change the chemical surface of the nanoparticles so they do that on their own. So the assembly is essentially controlled by the chemistry of the particle. we don't have to do anything. We impart some kind of chemical surface to the particle...and let them organize themselves."[26]

This language includes the key components of self-assembly that I previously established: a structure is built that depends on the information contained in the subunits of that structure, in this case the chemistry of the nanoparticle's surface, and there is no human intervention. Yet in observing the lab, what is singularly apparent is that "We don't have to do anything" and "we… let them organize themselves" can only be

26. Interview with NanoEngineering professor, November 14, 2012.

understood as a very limited kind of relative, technical statement defined against the top-down approach of placing each particle individually by hand. In fact the humans in the laboratory are doing a lot to produce the conditions that guarantee that the particles will organize themselves according to the one possibility open to them. The "hand" of Whitesides' statements and the "finger" of this statement stand in for the individual manipulation of each component, which does not happen with self-assembly. Only in this sense is there "no hand" at work in the subsequent assembly. Even though the individual particles are not being individually placed one at a time by an instrument, the self of self-assembly nevertheless refers to these individual particles, resting on a metaphysical and a methodological individualism of discrete preexisting particles forming into functional structures. The individual is still the subject of this narrative, even though the individual cannot be serially manipulated. What can be manipulated, though, is the environment, or the set of conditions within which these individuals form into specified structures. The fact that people "design" and "launch" the self-assembly, to recall Whitesides' 1995 comments, is not insignificant.

Nanoengineering students are taught that nano is all about bottom-up rather than top-down, and this distinction which valorizes bottom-up is reinforced in lecture, lab, and literature.

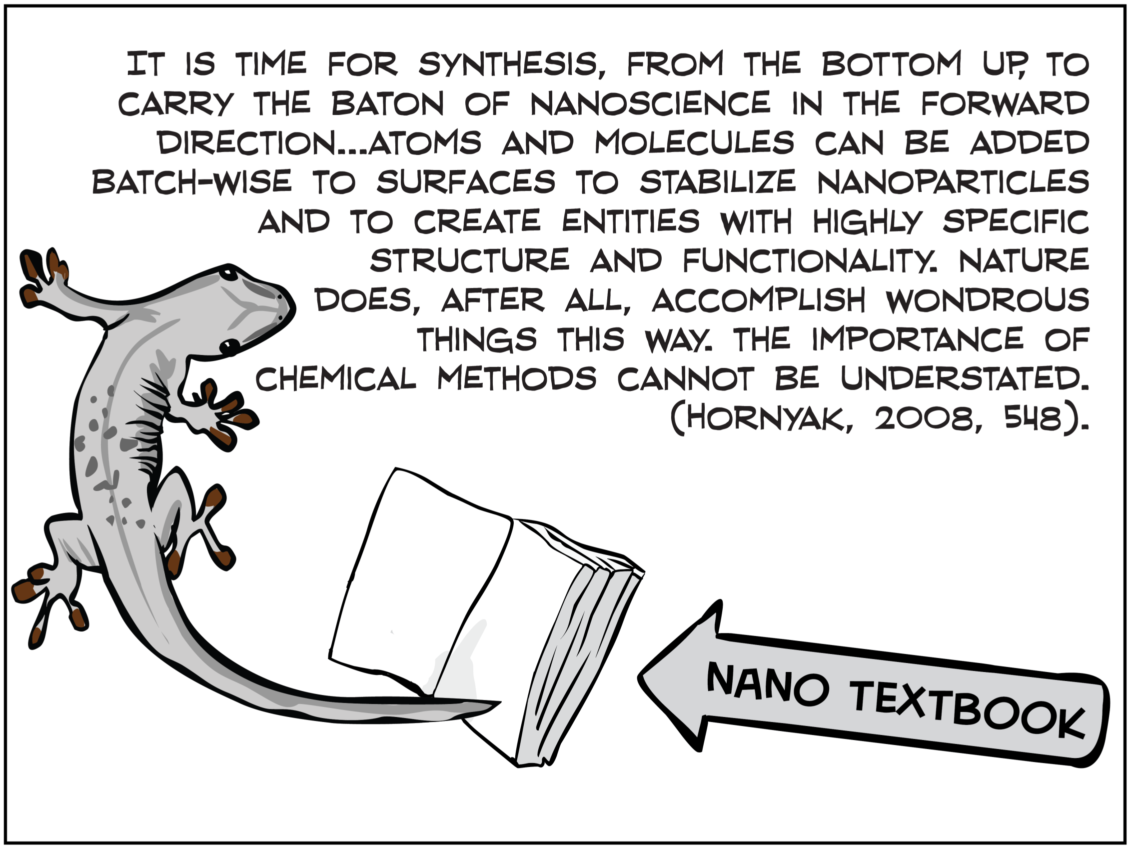

Illustration 89 Bottom-up. "It is time for synthesis, from the bottom up, to carry the baton of nanoscience in the forward direction…Atoms and molecules can be added batch-wise to surfaces to stabilize nanoparticles and to create entities with highly specific structure and functionality. Nature does, after all, accomplish wondrous things this way. The importance of chemical methods cannot be understated."[27]

Bottom-up is framed as more efficient, more cost-effective, and in the case of the nanoscale, necessary in order to get individuals into close-packed structures. If top-down is framed as using a hand—human or robot—then bottom-up is understood as no hand, or at least perhaps an "invisible hand." But what I see in observing self-assembly are the hands involved in producing it, even if these hands are not serially manipulating each individual. In one case, I observed four hands—those of a postdoc and an undergrad—

27. Gabor L. Hornyak, *Introduction to Nanoscience*, Boca Raton: CRC Press, 2008, 548.

engaging in an incredible performance of nanocube synthesis that involved precisely timed and honed embodied interactions with beakers, pipettes, timers, thermometers, and elements. Any inconsistency in temperature, the timing of adding specific elements, the pressure with which an element is forced out of the pipette and into the beaker, or any other aspect of this process results in inconsistent or failed results: the resulting nanocubes, or individuals, will not self-assemble correctly. Many times I observed results that were not satisfactory; according to the color or consistency, the members of the lab were able to determine that they had not been successful.

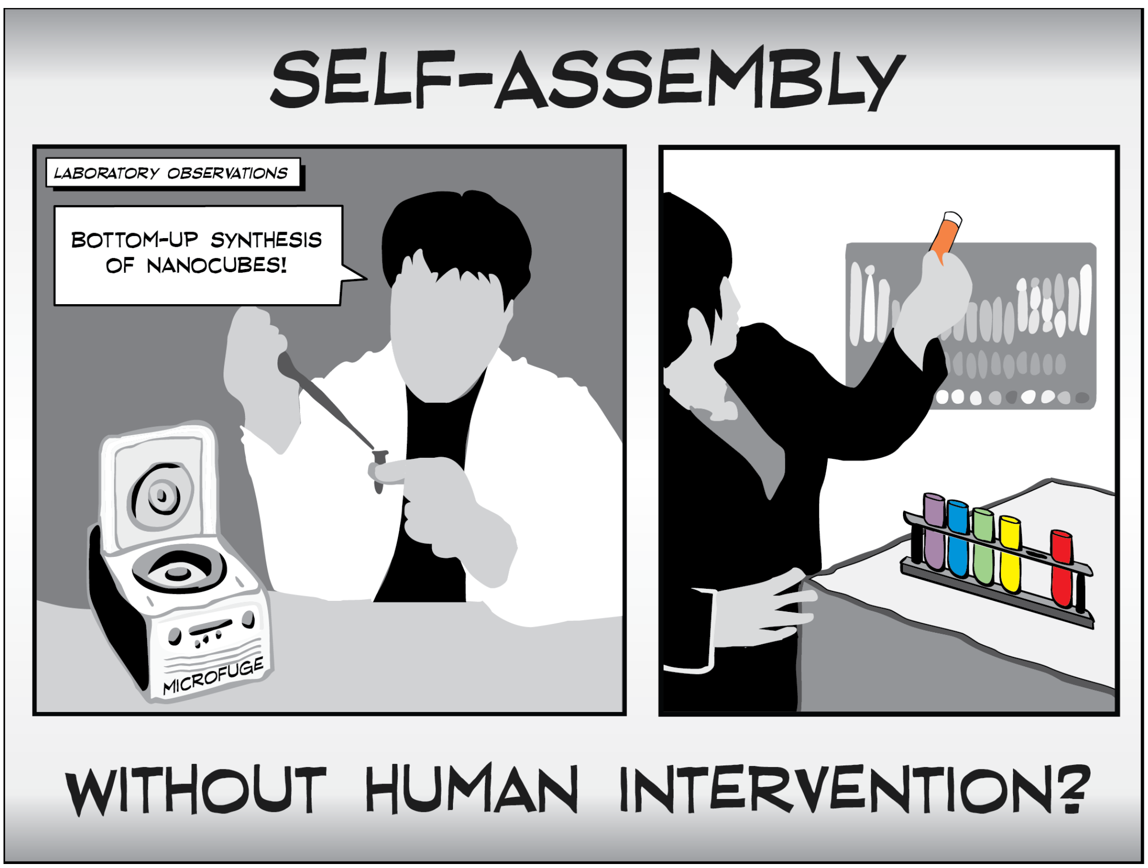

Illustration 90 Self-assembly without human intervention?

Self-assembly is only viable for nanomanufacturing if it is predictable, and it is only predictable when the nanoengineer achieves near complete control of the process. The individual particles may not require human intervention or hand once they are set into motion, but their organization into larger functional structures is hardly an autonomous process. Like political forms of governance, the individual particles are governed at a distance rather than through a hierarchical, top-down mode. These individual particles might even be said to be disciplined, their spatial and temporal organization optimized and made maximally efficient, the mechanisms of disciplinary power invisible—unless one steps into the lab to watch.

Self-assembly as a strategy of nanomanufacturing is one concrete way in which nanoengineers in my site understand nanoengineering as a biomimetic practice. Students learn early and often that what they are doing is just like what nature is doing, from the statement in the nanotechnology textbook cited in Chapter One indicating that nanotechnology is billions of years old if nature is counted[28] to descriptions of cellular reproduction in terms of self-assembly such as those I've just described. Bernadette Bensaude-Vincent and Sacha Loeve among others demonstrate how the concept of nature invoked by scientists is one that is already inscribed by their world views.[29] Certainly descriptions of cells as collections of functional self-assembled structures belies a mechanist view of the universe. And if proteins are understood as nanomachines, then, as Whitesides explains, nanomachines are ubiquitous and should not alarm:

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28. Hornyak, *Introduction to Nanoscience*, 5, 13.

29. Bernadette Bensaude Vincent and Sacha Loeve, "Metaphors in Nanomedicine: The Case of Targeted Drug Delivery." [In English]. *NanoEthics* 8, no. 1 (2014/04/01 2014): 1-17.

> As for ravaging the earth: in a sense, collections of biological cells already *have* ravaged the earth….Cells—self-replicating collections of molecular nanomachines—completely transformed the surface and the atmosphere of our planet. We do not normally think of this transformation as "ravaging the planet," because we thrive in the present conditions, but an outside observer might have thought otherwise.[30]

That is, on one hand, nanomachines in nature could be considered dangerous if imagined from a radically alterior perspective, but from a human standpoint it can only be seen as benign. And if it is benign in nature, then by implication human-made nanomachines should be considered no more threatening or dangerous. Recall in my brief discussion of Illustration 29 *The Scale of Things* in Chapter 3, reproduced below as Illustration 43, I pointed out the ways in which natural and manmade things are reinforced as simultaneously same and different.

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30. George M. Whitesides, "The Once and Future Nanomachine," *Scientific American* 285, no. 3 (September 2001): 79.

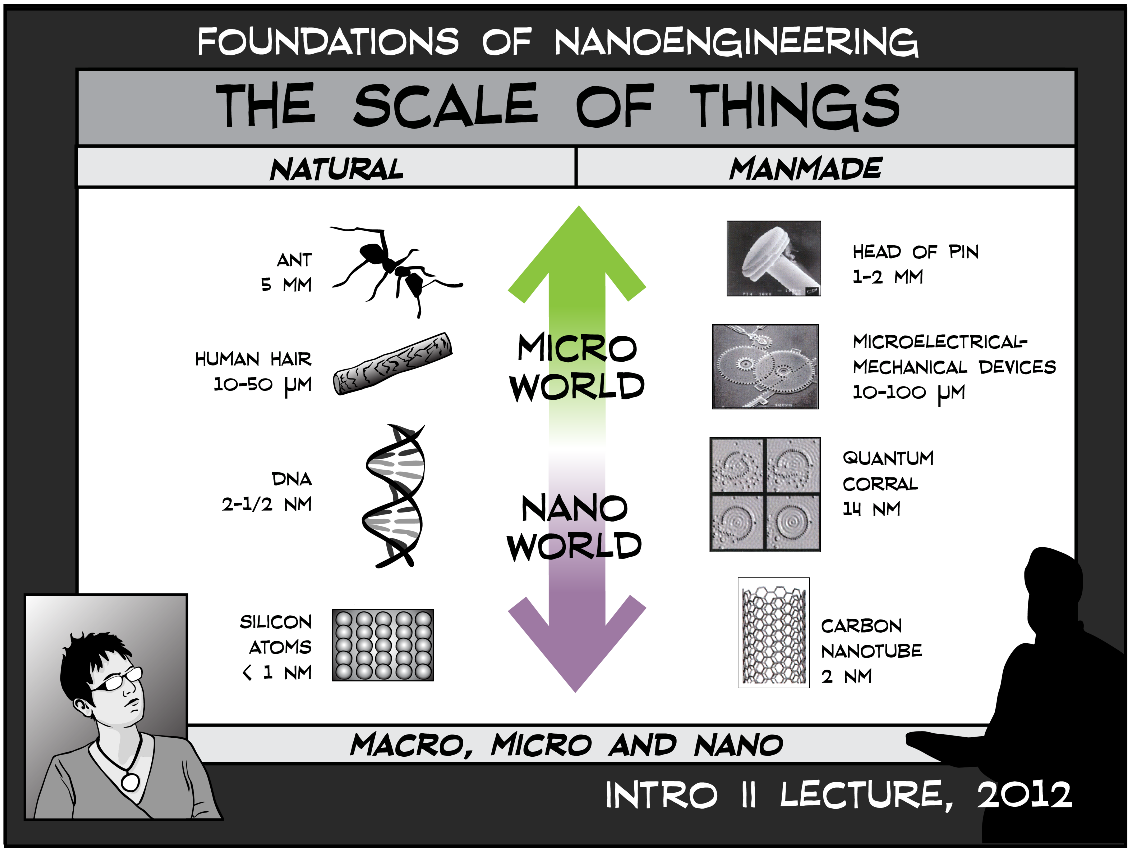

Illustration 91 The scale of things.

Feminist scholars have long insisted on the problematic nature of presuming distinct and static boundaries between nature and culture, of using nature as a material and moral resource, and of reinscribing social constructs into what counts as nature, all moves that underlie biomimicry.[31] Specifically, the notion that nature is already nano is used by nanotechnology enthusiasts to suggest that it is safe. While fears of self-replicating nanoassemblers gone amok have been largely discredited—and this is what Whitesides was addressing above in discussing nanomachines ravaging the earth—the appeal to

31. See, for example, Haraway *Primate Visions* and Barad *Meeting the Universe Halfway* (particularly her discussion of biomimicry, 364-9).

nature to make this argument relies on nature's presumed moral authority and assumptions about the sameness of nature's and man's engineering that underlie mimicry.

Yet in observing students learning how to use the Langmuir-Blodgett technique in their senior capstone class, what is remarkable to me is that the bottom-up and biomimetic aspects of this process are not intuitively bottom-up or biomimetic; in fact, the assembly of these selves is entirely invisible to the human eye. Students are taught to understand that what is occurring is the bottom-up and biomimetic assembly of individuals; they are learning a professional vision that sees this. A set of abstracted, representational results indicate whether self-assembly did or did not occur. For it to have occurred successfully, students need to have successfully executed on a complicated set of technical practices. Sometimes their attempts failed for a variety of reasons, all of which suggested an error in creating the structural, environmental conditions that would make self-assembly possible and predictable.

Market Governance

In my brief history of self-assembly, I focused on scientific literature from the 1950s forward that invoked the term. However, scientific ideas do not occur in a vacuum; at the same time, we might focus on shifting political ideas that, though they may not have used the term "self-assembly" nevertheless championed individualism, autonomy, self-organization, and a kind of biomimetic logic. Namely, I am referring to the emergence in the 1930s and 1940s of a neoliberal thought collective that believed that the conditions for the good society needed to be actively created, that the market is a kind of information processor more powerful than the human brain, that the market society must be treated as natural even as the conditions that enable it must be constructed, and that freedom is enacted by autonomous self-governed individuals.[32] I want to briefly show how self-assembly maps onto neoliberal notions of markets and governance, as a logic of rational individuals organizing without human intervention into optimal structures of information exchange. Philip Mirowski outlines a post-World War II shift in economic thinking emerging from Mont Pelerin and from Chicago, and partly informed by cybernetics, that comes to see the market as nature's ideal information processor that, while requiring particular conditions for its existence, essentially cannot be controlled, or planned.

32. Philip Mirowski and Dieter Plehwe, *The Road from Mont Pèlerin : The Making of the Neoliberal Thought Collective*, Cambridge, Mass.: Harvard University Press, 2009,1-469. Plehwe writes that the term originates in the 1930s (12), although the Mont Pelerin Society does not form until 1947. Mirowski articulates the key tenets of the neoliberal thought collective, some of which I have paraphrased here (434-440). They both use the term "thought collective" which comes from Ludwig Fleck.

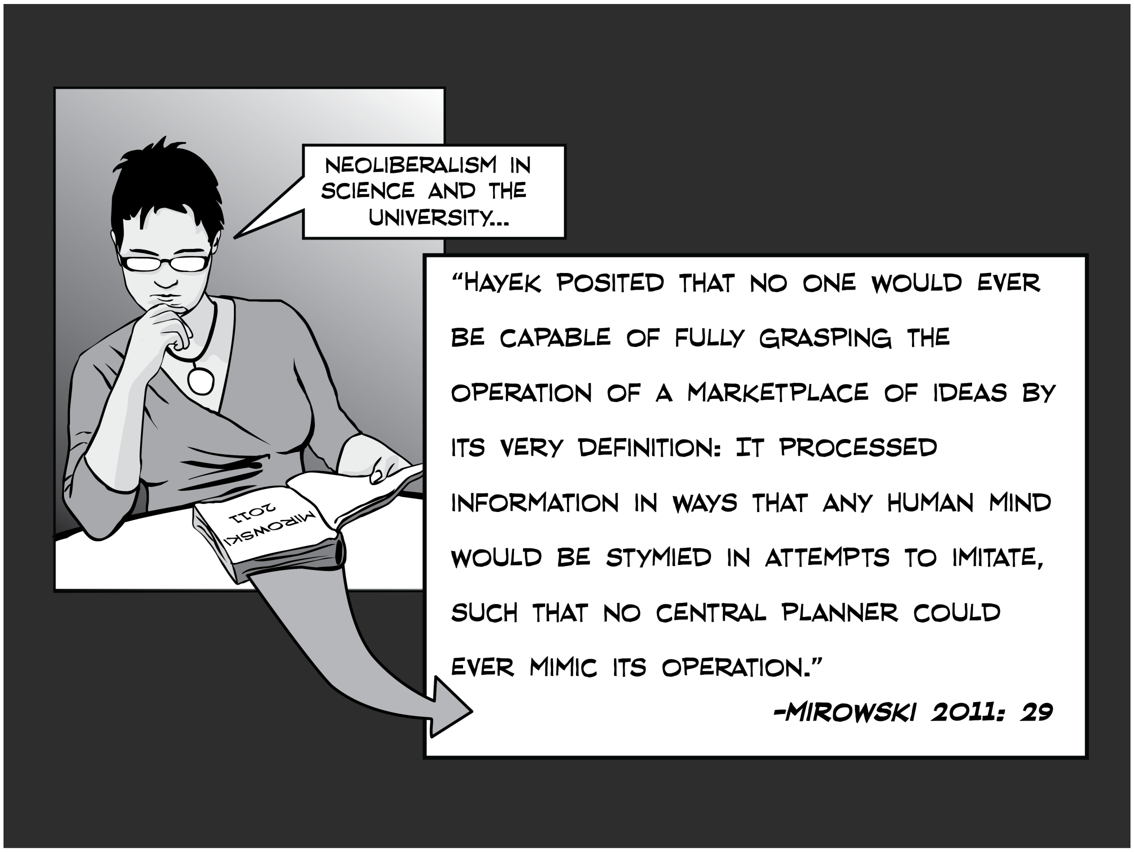

Illustration 92 Mirowski on Hayek. He writes: "Hayek posited that no one would ever be capable of fully grasping the operation of a marketplace of ideas by its very definition: It processed information in ways that any human mind would be stymied in attempts to imitate, such that no central planner could ever mimic its operation."[33]

Where the nanoparticles cannot be serially manipulated because the scale eclipses the spatial and technological abilities of the human (or robotic) hand, in this political and economic thought the information units processed by the market cannot be serially manipulated because the complexity of processing such a massive amount of disparate information would exceed the human mind. In this economic logic government is necessarily limited to creating and maintaining the necessary conditions for the market

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[33] Philip Mirowski, *Science-Mart : Privatizing American Science*, Cambridge, Mass.: Harvard University Press, 2011, 29.

but cannot do what the market superbly does on its own, which is to process information optimally and efficiently. Similarly, nanoengineers create the conditions within which nanoscale structures will assemble into predictable structures, but do not pick and place individual nanoparticles. The nanoparticles rely on information already contained within their immediate environment to assemble accordingly.

There is also similarity in understandings of autonomy and individualism—which in the case of neoliberal theory is grounded in classical liberal ideas. Freedom, within neoliberal thought, is posited in terms of "autonomous self-governed individuals, all naturally equipped with a neoclassical version of rationality and motives of self-interest."[34] In self-assembly, the nanoparticles are also viewed as autonomous, operating without human intervention. And, while they may not be attributed with self-interest or rationality per se, the process is described as rational, efficient, and functional, with each individual assembling into an optimal arrangement. As I've already suggested, self-assembly and the market each operate under the regime of what might be considered the "invisible hand": rational individuals organize into optimal, functional structures, operating spontaneously without intervention, exchanging information, exercising a kind of freedom. What distinguishes this from neoclassical thought, however, is precisely the effort that goes into creating the conditions necessary for the market, and the individuals, to operate in a predictable fashion.

What I am suggesting is not that nanoengineers, or the biologists and chemists from the 1950s on, have consciously or rationally taken up neoliberal philosophy, but that

34. Ibid., 30.

particular assumptions about nature and man—rooted in Enlightenment thought, and developing particularly from the 1930s on by proponents of neoliberalism—are recognizably manifest in technoscientific understandings of both markets and matter. In both cases—the individual nanoparticles self-assembling and the individual rational actors pursuing their own interests in the marketplace—these assumptions of autonomy obscure relational modes of being and the power dynamics that are naturalized in the processes of engineering and governance.

Self-Assembling Nanoengineers

Taking the rhetoric of self-assembly seriously, I couldn't help but to notice the nanoengineering students in the lab who were, week after week, synthesizing nanocubes and other nanoscale structures for self-assembly experiments. Could the same assumptions about nature and man and the ubiquity of self-assembly across scales also inform implicit understandings of how undergraduate students were expected to assemble into the larger, functional structures of the department and university? And if so, what was the desired functional outcome? From their first one-credit course as first-year students, when their class final was to develop their individual four-year plans toward graduation, to their final two-quarter capstone sequence as fourth-year students choosing their own laboratory projects, I observed the disciplinary power at work in constituting them as autonomous individuals while at the same time creating the conditions that ensured a fairly predictable outcome. That is, in addition to harnessing the productive power of nano dreams and the excitement of thinking about how smaller is better, to recall examples I elaborated on in Chapters 2 and 3, the department invests in producing the conditions that will ensure not only graduates of the program but a workforce for the nanotechnology industry.

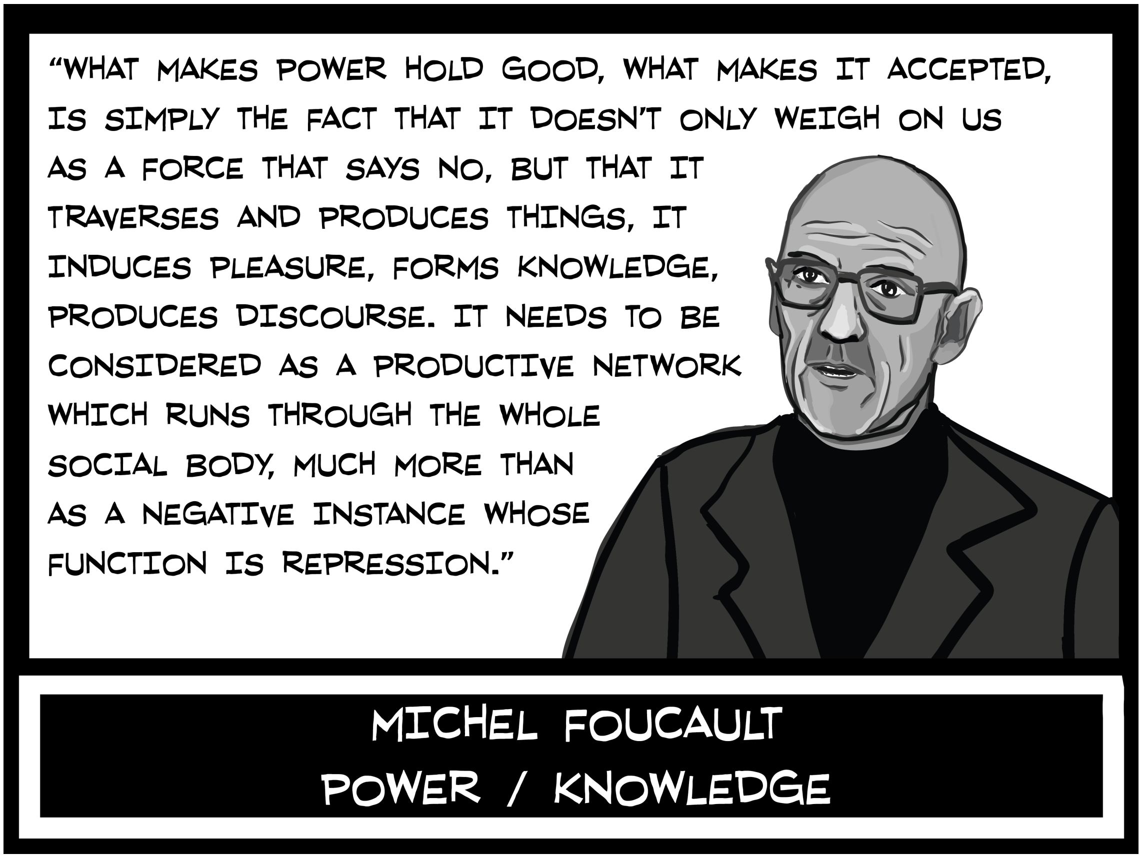

Illustration 93 Foucault on disciplinary power. "What makes power hold good, what makes it accepted, is simply the fact that it doesn't only weigh on us as a force that says no, but that it traverses and produces things, it induces pleasure, forms knowledge, produces discourse. It needs to be considered as a productive network which runs through the whole social body, much more than as a negative instance whose function is repression."[35]

Sometimes this occurs by happenstance, resulting from constraints of time, money, equipment, and institutional requirements. For example, while students could freely choose how to assemble their four-year plans, and were given the necessary information to do so, there were in fact few variations that could result in a successful completion in

35. Michel Foucault and Colin Gordon, *Power/Knowledge : Selected Interviews and Other Writings, 1972-1977*, New York, N.Y.: Pantheon Books, 1980, 119.

four years. Indeed, the chair of the department stressed to them that they needed to prioritize the department requirements and the particular sequence of prerequisites, and fit their general education requirements in over the summer if need be, in order to finish on time.[36] Likewise, in their fourth year laboratory class, they were able to design their own research projects. Yet, given the constraints of time, resources, and skillsets of the teams they were placed with, many found that their original ideas were not tenable, and in the end a relatively narrow range of projects were enabled according to the conditions of the lab.

More importantly, students were presented with few variations on what constitutes a successful nanoengineer. They were encouraged to think and be entrepreneurial, to identify market opportunities and constraints, and to embrace teamwork (all of which I will expand on in Chapter 5), and to pursue their nano dreams (which I discussed in Chapters 2 and 3, and will return to in Chapter 5). Yet the desired functional outcome was fairly explicitly stated to them in class and in the department proposal: to produce the workforce for a new industry. Indeed, through the lens of self-assembly, it seems that students can very well be seen as autonomous individuals who contain the necessary information and are able to obtain the necessary energy from the environment to assemble into the larger, hierarchical, functional structures of high tech innovation with a high degree of predictability.[37] And, like self-assembly in the laboratory, from one perspective this may be bottom-up. From another perspective,

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36. I observed this in an introductory NanoEngineering course, two years in a row, 2011 and 2012.

37. Unfortunately, I do not have data about students' career trajectories following graduation. I can roughly say, based on my interviews, that the majority of students I spoke with were attempting to get a job in nanotechnology, and a minority were attempting to go to graduate school.

however, there is an extraordinary effort involved in creating the conditions that enable and constrain this assembly to achieve the desired outcome. This is something I will explore in more detail in the next chapter, albeit under the guise of a different metaphor: human capital.

Conclusion

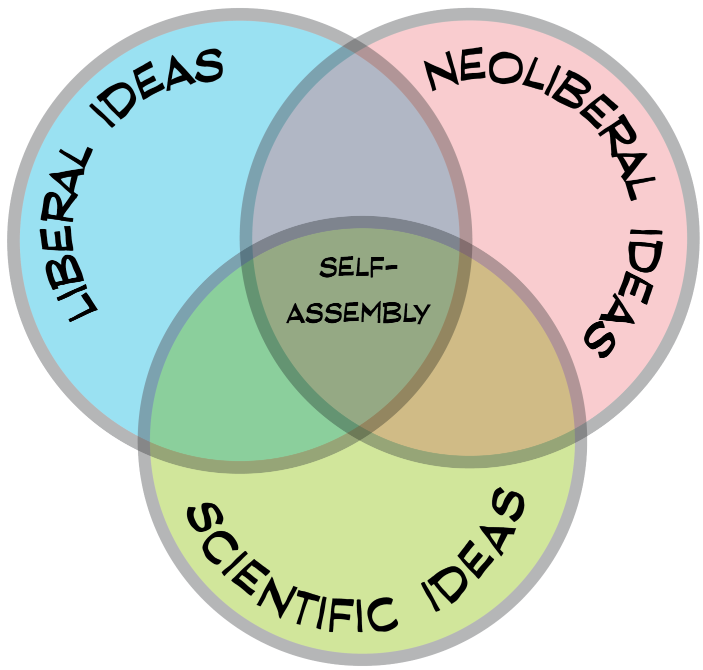

Illustration 94 Situating self-assembly.

What would nanoengineering be if it did not predicate itself on man mimicking nature, individuals self-assembling, and bottom-up replacing top-down? I think in order to explore this question further, the invisible hand needs to be made visible, to examine how nanoengineering as an economic imperative works through the material and discursive practices of nanoscale research. Self-assembly, with its assembly metaphor that inscribes Taylorist ideals of manufacturing into the process, simultaneously emphasizes autonomy and control—nanoengineering are attempting to control self-assembly so that the autonomous nanoparticles will predictably assemble into the desired structures. While nanoengineers tend to be explicit about their aspirations for material control, examining this in the context of the metaphysical assumptions of self-assembly re-centers important questions for the social and ethical dimensions of nanotechnology: Who gets to control, for whom and what will atomic and precise material control constitute benefit and harm, and what politics will be inscribed into the nanotechnology artifacts that emerge from this research? When profit is the one certain thing, the only thing without a question mark, we might expect that nanotechnologies will be assembled from the bottom-up as embodied structures of these market logics. And what kinds of autonomy will the human individuals of this new discipline achieve? The answer to this question may depend on the dynamics of labor stratification: will they become the lab technicians of an industrial lab, or will they become professors and/or entrepreneurs? I explore this in more depth in the next chapter.

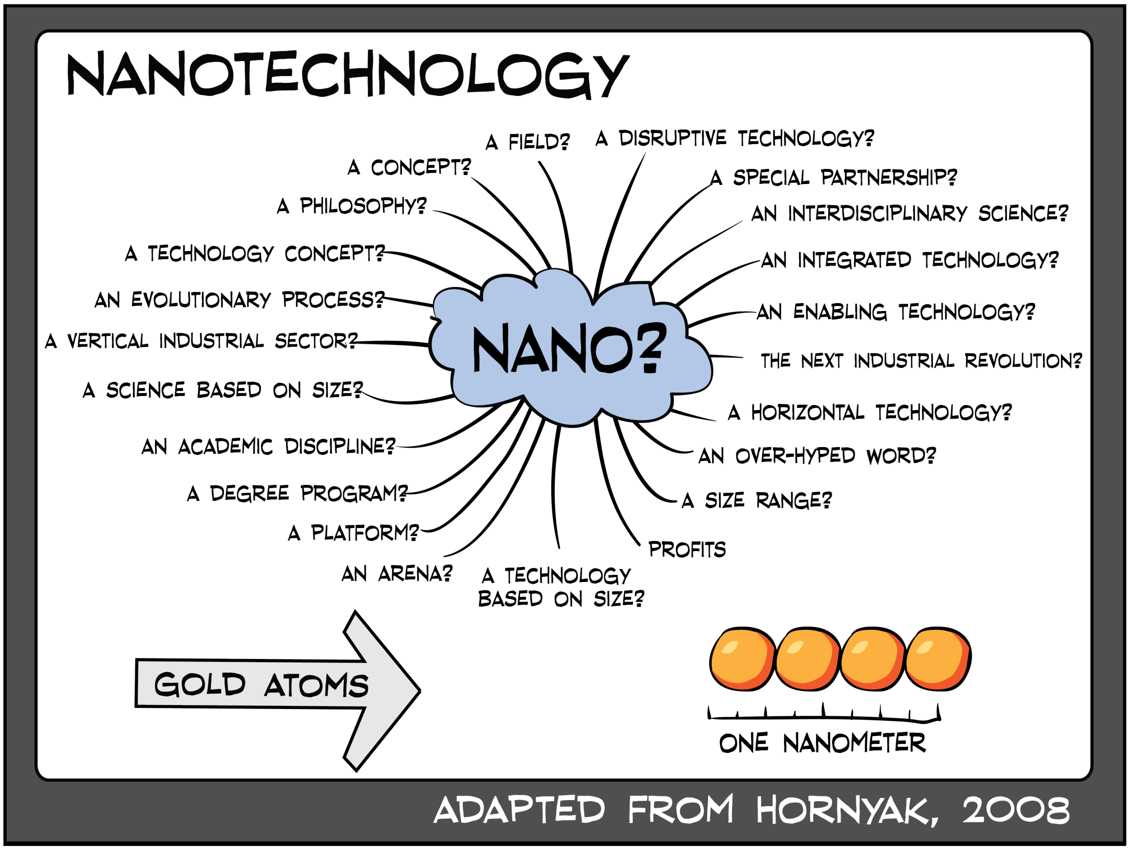

Illustration 95 Nano profits. This image, based on an illustration in a nanotechnology textbook answers the open-ended question "Nano?" with many more questions. But one answer has no question mark: profits.

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Chapter 5 Producing Human Capital for a New Industry

> As it dispenses with the very idea of the public, neoliberal rationality recognizes and interpolates the subject only as human capital, making incoherent the idea of an engaged and educated citizen.
>
> —Wendy Brown[1]

Introduction

In 1960, Clark Kerr, then President of the University of California, gave a speech in which he positioned the university as central to the "knowledge industry" that he hoped would "serve as the focal point for national growth" in the second half of the twentieth century.[2] Amidst the anxiety of the Cold War, just three years after the Soviet Union launched Sputnik 1, Kerr said:

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1. Wendy Brown, *Undoing the Demos: Neoliberalism's Stealth Revolution*, First Edition, ed. New York Cambridge, Massachusetts: Zone Books MIT Press, 2015, 183.

2. Clark Kerr as seen on *Berkeley in the Sixties*. Mark Kitchell, "Berkeley in the Sixties," United States: Kitchell Films in association with P.O.V. Theatrical Films, 1990.

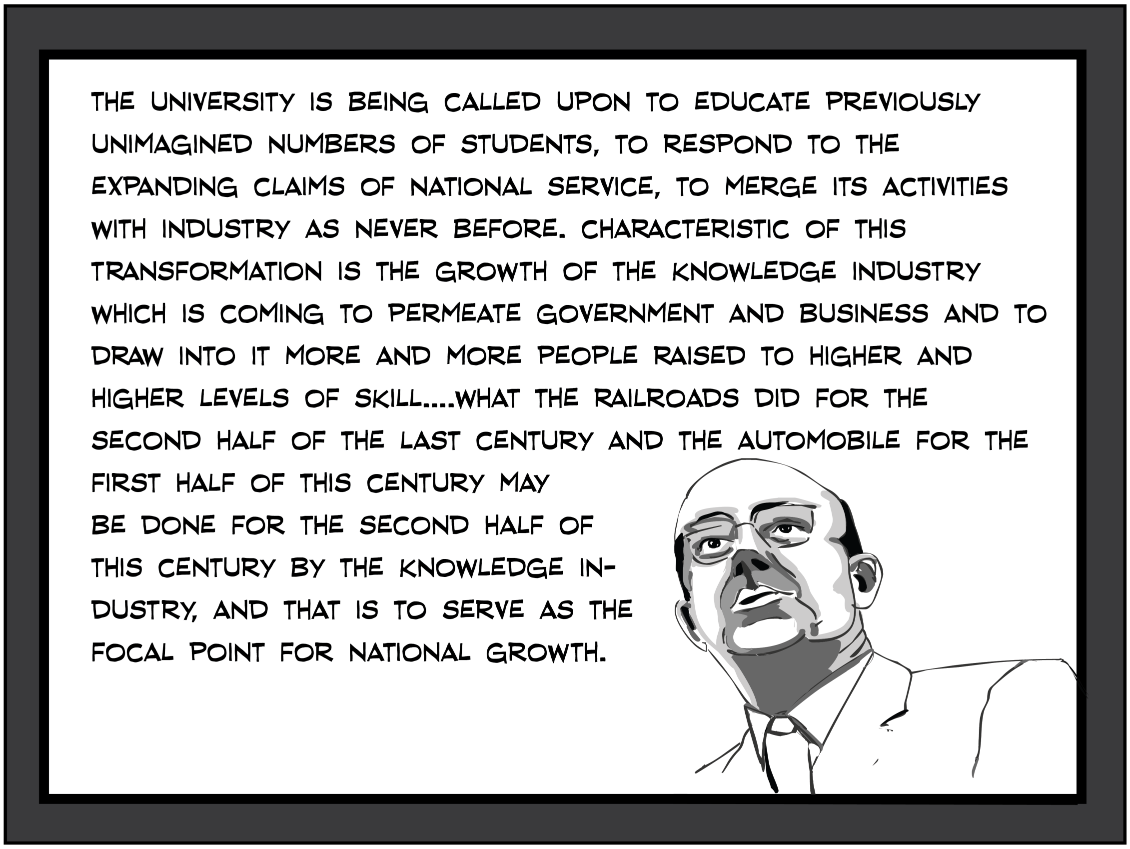

Illustration 96 Clark Kerr. "The university is being called upon to educate previously unimagined numbers of students, to respond to the expanding claims of national service, to merge its activities with industry as never before. Characteristic of this transformation is the growth of the knowledge industry which is coming to permeate government and business and to draw into it more and more people raised to higher and higher levels of skill….What the railroads did for the second half of the last century and the automobile for the first half of this century may be done for the second half of this century by the knowledge industry, and that is to serve as the focal point for national growth."[3]

Refiguring the university as the key institution of a new industry would, Kerr hoped, make it a dominant economic engine. What today might easily pass without controversy was then challenged by students at UC-Berkeley. One of the most famous orators of the Free Speech Movement—Mario Savio—vociferously rejected the notion that the university should be a knowledge factory:

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3. Clark Kerr as seen on *Berkeley in the Sixties*. Mark Kitchell, "Berkeley in the Sixties," United States: Kitchell Films in association with P.O.V. Theatrical Films, 1990.

> Well I ask you to consider: if [the university] is a firm, and if the board of regents are the board of directors, and if President Kerr in fact is the manager, and I tell you something: the faculty are a bunch of employees and we're the raw materials. But we're a bunch of raw materials that don't need to have any process upon us, don't mean to be made into any product, don't mean to end up being bought by some clients of the university, be they government, be they industry, be they organized labor, be they anyone. We're human beings![4]

Emphasizing that the students of the University of California are human beings, he highlighted the dehumanizing possibilities of the university's corporatization and challenged Kerr's implicit designation of students as the raw materials that should be transformed into products by the university. Yet in 2010, fifty years later, incoming students to UC San Diego's Jacobs School of Engineering and their parents sat quietly and respectfully as the Dean welcomed them with words that were much more pointed than those of Kerr. He said that the role of a research engineering school is:

> Mainly to provide the human capital and to provide the intellectual capital, and the choice of words is very important. I'm not talking about human resources and intellectual property. I'm talking about human capital and intellectual capital. If we are not educating students that are marketable after they finish here, then we are doing not the right job, okay. *So you are our most important product, you are the capital we should be generating*.[5]

Here, the students are explicitly hailed as products, as a type of capital produced by the university. It is no longer merely implied. Indeed, these words are part of the Jacob School's Vision Statement: "The Jacobs School will provide the human capital and the intellectual capital to drive our innovation society."[6] These are students who are to be

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4. Mario Savio as seen on Mark Kitchell's *Berkeley in the Sixties*, 1990.

5. Dean, Jacobs School of Engineering, Admit Day Speech, April 9, 2011, transcribed by author, emphasis added.

6. http://www.jacobsschool.ucsd.edu/about/mission.sfe, accessed June 29, 2015.

educated to be marketable and to contribute to an innovation economy. The dean distinguishes between human resources and human capital, and between intellectual property and intellectual capital, suggesting there is an important distinction to be made in identifying each as capital. Capital, rather than resources or property, is the marketable and useful product coming out of the university, whether in the form of laboring bodies, patented knowledge, or material technologies. Capital in particular must continually attract investors and accumulate more capital.

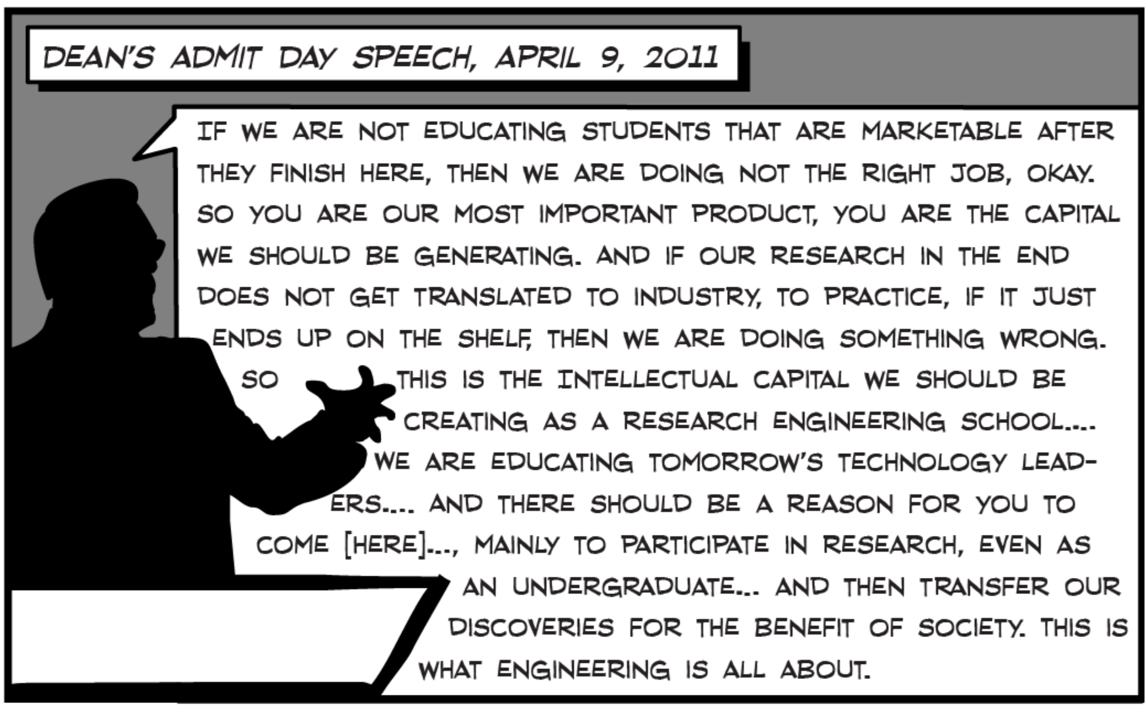

Illustration 97 Dean's Admit Day speech. "If we are not educating students that are marketable after they finish here, then we are doing not the right job, okay. So you are our most important product, you are the capital we should be generating. And if our research in the end does not get translated to industry, to practice, if it just ends up on the shelf, then we are doing something wrong. So this is the intellectual capital we should be creating as a research engineering school…We are educating tomorrow's technology leaders…and there should be a reason for you to come [here]…, mainly to participate in research, even as an undergraduate…and then transfer our discoveries for the benefit of society. This is what engineering is all about." April 9, 2011. Transcribed by author.

As I will elaborate in this chapter, and building on the work of Michel Foucault and Wendy Brown, the explicit production of human capital in particular is linked to the responsibilization of the individual worker and the concomitant precarity of her capital valuation.[7] The concept of human capital, first articulated by Adam Smith, was reintroduced in the late 1950s and early 1960s by Jacob Mincer, Ted Schultz, and Gary Becker—economists associated with the Chicago School of Economics and neoliberal theory.[8] Becker, writing in 1964, states:

> Schooling, a computer training course, expenditures on medical care, and lectures on the virtues of punctuality and honesty are capital too in the sense that they improve health, raise earnings, or add to a person's appreciation of literature over much of his or her lifetime. Consequently, it is fully in keeping with the capital concept as traditionally defined to say that expenditures on education, training, medical care, etc., are investments in capital…However, these produce human, not physical or financial, capital because you cannot separate a person from his or her knowledge, skills, health, or values the way it is possible to move financial and physical assets while the owner stays put.[9]

That is, human capital is capital that is embodied and inseparable from the person who has it, but importantly, it can be invested in. While Becker indicates that a "person's appreciation of literature" might index their capital as well, not surprisingly, this is not an

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7. Wendy Brown, *Undoing the Demos: Neoliberalism's Stealth Revolution*, First Edition, ed. New York Cambridge, Massachusetts: Zone Books MIT Press, 2015; Michel Foucault, Michel Senellart, and Collège de France, *The Birth of Biopolitics : Lectures at the Collège De France, 1978-79*, Basingstoke [England]; New York: Palgrave Macmillan, 2008. By responsibilization, she is referring to an idea and practice of "forcing the subject to become a responsible self-investor and self-provider" (84).

8. Gary Becker, *Human Capital; a Theoretical and Empirical Analysis, with Special Reference to Education*, National Bureau of Economic Research General Series, New York,: National Bureau of Economic Research; distributed by Columbia University Press, 1964. Milton Friedman is also listed as one of the "pioneers in this field" of human capital by Gary Becker in his preface to the third edition of *Human Capital* (xix).

9. Becker, *Human Capital,* 15-16.

attribute that makes it into the equation for measuring human capital. The equation takes into account valuations of earnings, amounts invested, and returns on investment. Becker defends his theory, saying:

> My friends in the humanities like Dick Stern may complain that so far I have only mentioned "money," or they might say "mere money." Is there any place in human capital theory for education to appreciate literature, culture and the good life? Fortunately, nothing in the concept of human capital theory implies that monetary incentives need to be more important than cultural and nonmonetary ones.[10]

Yet while there may be nothing in the concept that implies a greater value for monetary incentives, there is something in the equation that necessitates it: the fact that nonmonetary incentives are excluded from it, which is not surprising since these cannot be so easily quantified or measured. Human capital theory posits that knowledge and skills become embodied in persons, and this is measured in terms of incomes, or returns on capital[11]—it is the person's economic valuation in the marketplace that indexes their capital worth.

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10. Ibid., 22.

11. Foucault, *The Birth of Biopolitics*, 224. Foucault defines income as a return on capital.

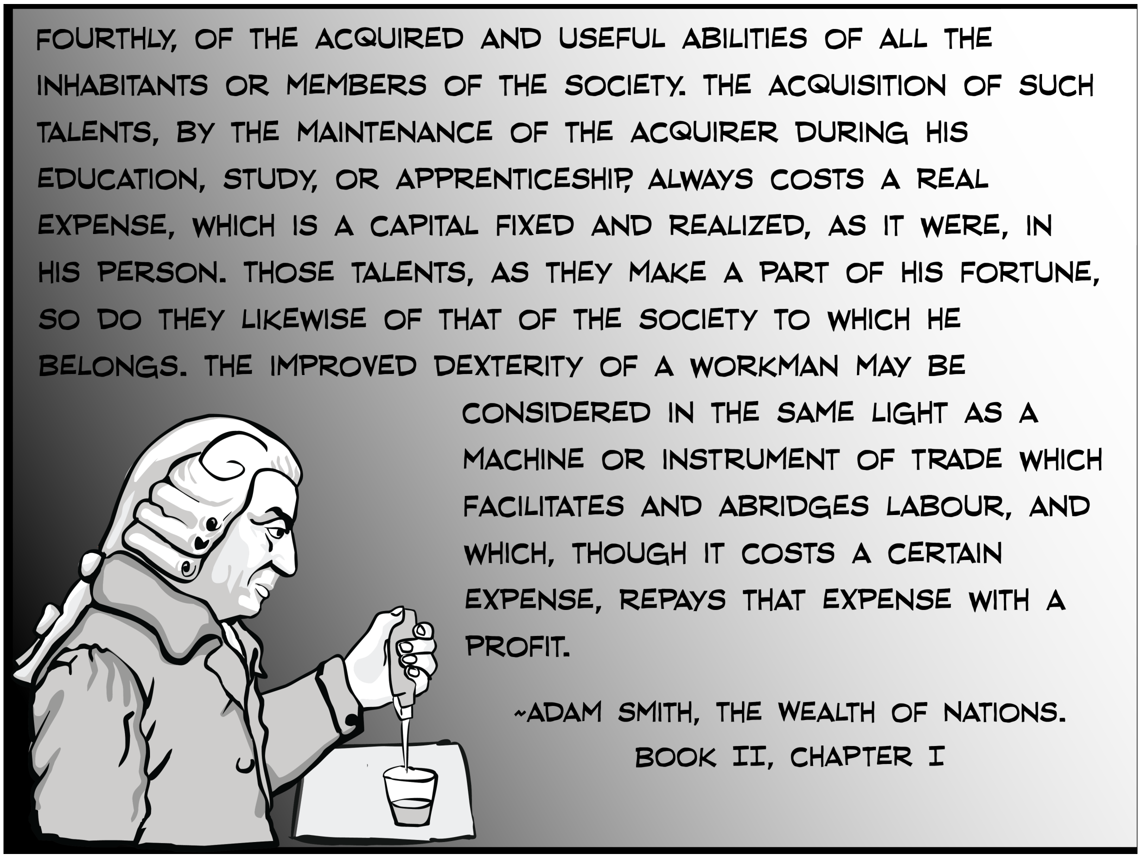

Illustration 98 Adam Smith on human capital.

For Adam Smith, human capital refers to the “acquired *and useful* abilities” of the person that “may be considered in the same light as the machine or instrument of trade which facilitates and abridges labour.”[12] Utility was also emphasized by the dean in his welcome comments, but while utility may be a key principle, what counts as useful is contingent. Indeed, what makes any attempt at calculating human capital possible is its reliance on the “present value of a person’s future expected earnings,”[13] terms that highlight its

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12. Adam Smith and Earnest Belfort Bax, *An Inquiry into the Nature and Causes of the Wealth of Nations, Volume 1*, G. Bell, 1892, reprint, 281, emphasis added.

13. Morgan Adamson, "The Human Capital Strategy." *ephemera* 9, no. 4 (2009): 273.

contingent character and that imply market mechanisms for valuation. As Foucault points out, human capital theory extends economic analysis into the domain of labor,[14] constituting the worker as an active economic subject and enterprise of himself who invests in his capital in part through education.[15]

While I did not interview students or parents following the dean's welcome speech, there were no visible protests or public challenges regarding these students being cast as capital. And, within a couple of years, the new nanoengineering undergraduate major had so many students that it appealed to the university for an "impacted" status that would give the department the power to cap its enrollment. It would seem through their actions that incoming students were willing to become human capital, though it is also possible that the words simply did not register.

In chapter 2, I showed how the nanoengineering identity is produced as intrinsically ethical in part through promissory narratives of nanomedicine saving lives. I argued that the good is articulated partially through the nano dreams that guide nanoengineering, which are the visions of nanotechnologically-enabled progress meant to universally benefit humanity. In encouraging students to pursue their nano dreams, nanoengineering students are hailed as entrepreneurial leaders whose individual goals and passions will underwrite innovation and societal benefit. Yet at the same time students are told that the new industry needs bachelor degrees, not just Ph.D.s, in order to become a successful industry. The majority of them are expected to become these bachelor

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14. Foucault, *The Birth of Biopolitics*, 219-20.

15. Ibid., 223, 226.

degrees, or in other words, the technically proficient but relatively cheap labor employed by industry. As such, they must necessarily work on the product roadmaps of those companies that employ them. I suggested that there was some tension between these two narratives of the entrepreneurial nano dreamer and the high tech laborer. In this chapter, I argue that the institutional goal of producing human capital manifests in the undergraduate curriculum primarily in the form of entrepreneurialism, and that the idea of human capital underlying this “entrepreneurial attitude” threads the needle between these two narratives.

Following a brief empirical analysis of entrepreneurialism in the curriculum, I offer a theoretical consideration of the implications of the engineering school’s goal of producing human capital. To the extent that the dean’s words and the Jacob School’s vision statement are seemingly uncontroversial, at least within the engineering school, what does this indicate about the commonsense consciousness of students, educators, and administrators whose daily practices are mediated through the institution? How might we understand the role of the nano dream, or the conviction that smaller is better, in light of the subsumption of both knowledge and labor production within the paradigm of capitalization and innovation? What kind of thinking is enabled or constrained by the logic of human capital, and what does this mean for students, the university, science, and democracy?

Learning Entrepreneurialism in the University

Teaching an attitude of entrepreneurialism is central to producing human capital. An attitude of entrepreneurialism is not necessarily the same thing as the concrete skills and practices of entrepreneurship, which students might learn in business school, but is instead an orientation to one's self and one's work that privileges the market, risk-taking, and capital accumulation. NanoEngineering students do not learn entrepreneurialism in any one class or event. Rather, they learn this orientation through exposure to competition and participation in competitions, through their participation in laboratories, internships, and start-up companies, and through faculty modeling this attitude in formal and informal contexts.

While Steven Shapin has argued that entrepreneurial science is nothing new,[16] within this nanoengineering undergraduate program, students don't go into the academy to learn science, then proceed to learn entrepreneurialism afterward. Rather, they begin to learn entrepreneurialism from the moment they come to Admit Day and are hailed as human capital and as students who will become entrepreneurial. This is often one of the first moments of a student's undergraduate life, taking place the spring prior to their fall matriculation. And it may be the first time—but certainly not the last—that a professor or administrator in their university articulates and naturalizes a cornerstone of the dominant ideologies that inform a neoliberal rationality: that which matters in the world can or should be able to exist as a form of capital.[17] At the most basic level, the lack of any

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16. Steven Shapin, *The Scientific Life: A Moral History of a Late Modern Vocation*, Chicago: University of Chicago Press, 2008.

17. Brown, *Undoing the Demos*; Foucault, *The Birth of Biopolitics*; Philip Mirowski, *Science-Mart : Privatizing American Science*, Cambridge, Mass.: Harvard University Press, 2011. I will further define what I mean by neoliberal rationality in my discussion of the university. For now, I am drawing primarily on Wendy Brown's articulation of neoliberal rationality as a distinctive mode of reason that constitutes all entities exclusively as capitals, Foucault's articulation of human capital in terms of entrepreneurship of oneself, and Philip Mirowski's analysis of neoliberal science, which focuses additionally on the role of a strong and active state in creating and maintaining markets and the infrastructures of innovation.

public response or controversy following the dean's welcome address signals that the rhetoric of human capital and the practices of understanding oneself as capital—even when this term may not be used—have become unremarkable. The dean continued in his welcome speech:

> It is another one of our goals to instill a little bit of an entrepreneurial spirit in you. This is where you will hopefully set yourselves apart from students from other places, to get that entrepreneurial spirit, to learn from failure, to be willing to take risks, okay, this is not something you get in other colleges, this is something we want to instill in you as our students.[18]

Here, entrepreneurialism is explicitly connected to competition and risk-taking, where entrepreneurialism itself is how these students/human capital will out-compete students from other institutions who are not learning entrepreneurialism. Wendy Brown shows how competition, rather than exchange, is the central principle at work in the processes of capital accumulation under neoliberal rationality:[19]

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18. Dean, Jacobs School of Engineering, Admit Day Speech, April 9, 2011, transcribed by author.

19. Brown, *Undoing the Demos*. Michel Foucault identified competition as the central principle at work in neoliberal rationality in *The Birth of Biopolitics*, 2007. See Brown, *Undoing the Demos*, 36, where she builds on this.

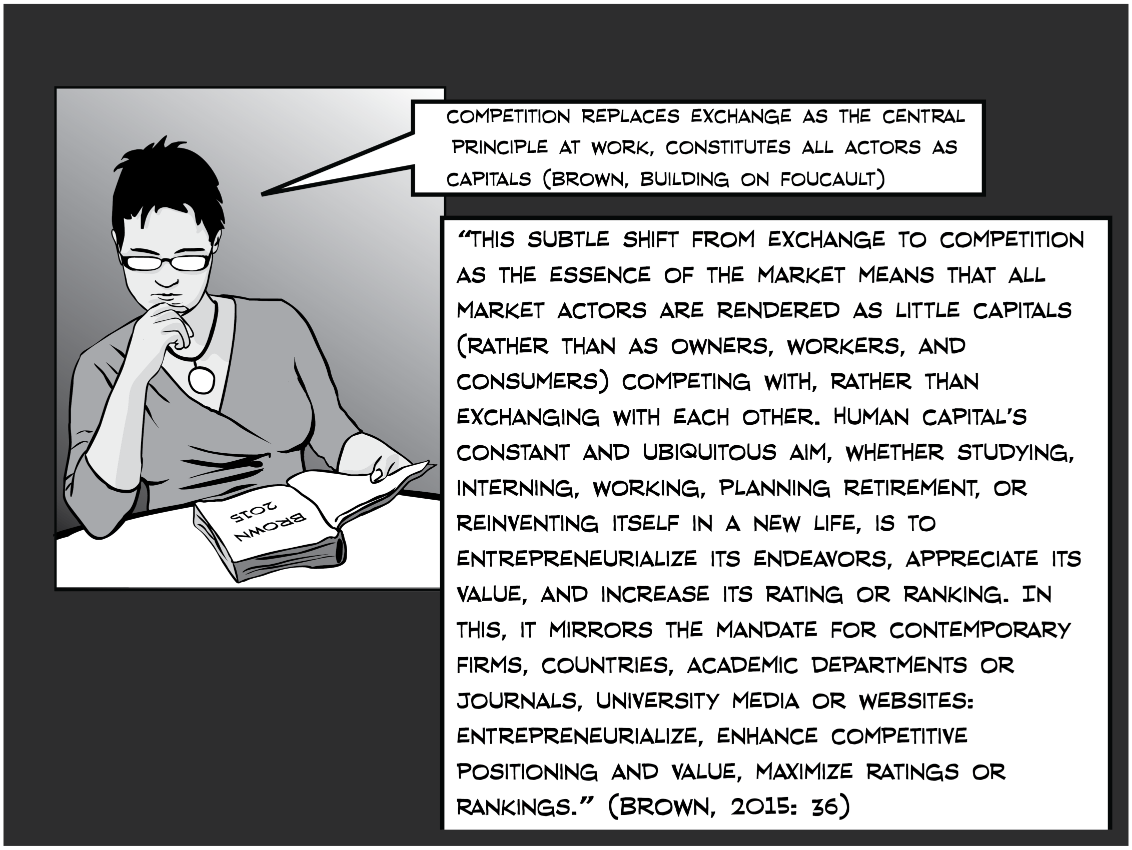

Illustration 99 Brown on competition. "This subtle shift from exchange to competition as the essence of the market means that all market actors are rendered as little capitals (rather than as owners, workers, and consumers) competing with, rather than exchanging with each other. Human capital's constant and ubiquitous aim, whether studying, interning, working, planning retirement, or reinventing itself in a new life, is to entrepreneurialize its endeavors, appreciate its value, and increase its rating or ranking. In this, it mirrors the mandate for contemporary firms, countries, academic departments or journals, university media or websites: entrepreneurialize, enhance competitive positioning and value, maximize ratings or rankings."[20]

Indeed, students not only become competitive by learning entrepreneurialism, they learn entrepreneurialism in part through competition. While students have reported to me that nanoengineering, as a newer major, is less competitive than bioengineering, students are nevertheless introduced to competition early and often. And, as the major grows, the

20. Ibid., 36.

competitiveness students feel within the major will likely grow as more students compete to be accepted into the major, and then for a limited number of laboratory positions.

Students are encouraged to participate in internships, laboratories, competitions and start-ups, each of which becomes a means of gaining real-world experience and of demonstrating their leadership and competitiveness as they build their capital and constitute themselves as self-investing capital. Unfortunately, there is a class dimension built into this as well: students who must maintain paying jobs in order to support themselves financially are not in a position to compete for unpaid internships and lab positions, or to contribute the extra time necessary to participate in competitions. As of this writing, I am able to count approximately fifty undergraduate positions in nanoengineering labs going to undergraduate nanoengineering students, but there are over nine hundred undergraduate nanoengineering students in the department.[21] Although it is possible that some will obtain positions in labs with professors from other departments, the numbers suggest a minority will obtain such a position. Additionally, the most competitive students will often have more than one lab position, thus reducing the number of positions further and making it even more competitive. Students are informed that they should not attempt to obtain a position if they do not first have a high GPA, because they need to be able to show that they can handle the workload and do well in their classes. While this makes sense, a student's GPA may also be adversely affected by their need to hold jobs outside of school, again making lab positions potentially more

21. According to the "2015 Snapshot" of the UC San Diego Jacobs School of Engineering, there are 912 undergraduate students in the NanoEngineering Department. http://jacobsschool.ucsd.edu/news/news_resources/docs/snapshot2015.pdf, accessed January 8, 2015.

available to students who can afford to work twenty hours per week unpaid. Obtaining a laboratory position is very important to getting an internship and certainly a job after graduation, and practically necessary for getting into a graduate program. Students who find placement in a lab are well-positioned to pursue such positions. However, without a lab position, students do not acquire a lot of laboratory experience, as the curriculum offers only a two-quarter laboratory capstone experience at the end of the fourth year.

Obtaining an internship is also challenging. One of the primary vehicles through which students locate and apply for internships is through the Team Internship Program, run through the Corporate Affiliates Program of the Jacobs School of Engineering. Here, students can browse postings for internships and submit their resumes to apply for them. Undergraduates can also build and maintain their profiles on an undergraduate research portal. Events on the research portal include items like the annual “Research Speed Dating Event” that matches undergraduates with research projects on the annual theme. Whether getting into the major, or obtaining a lab position or an internship, students who have more capital are better positioned to compete effectively, and invest in and accumulate their capital. And there is a link between lab positions and internships: without lab experience, it is extremely difficult to get an internship. For students who are not able to get into a lab, or for students who decide they don’t want to be in a lab environment, it is necessary to strategize around an alternative path toward getting experience. For example, this student indicates that having determined based on reports of friends that she would not enjoy working in the lab, she decided to shift her focus from bioengineering to materials science:

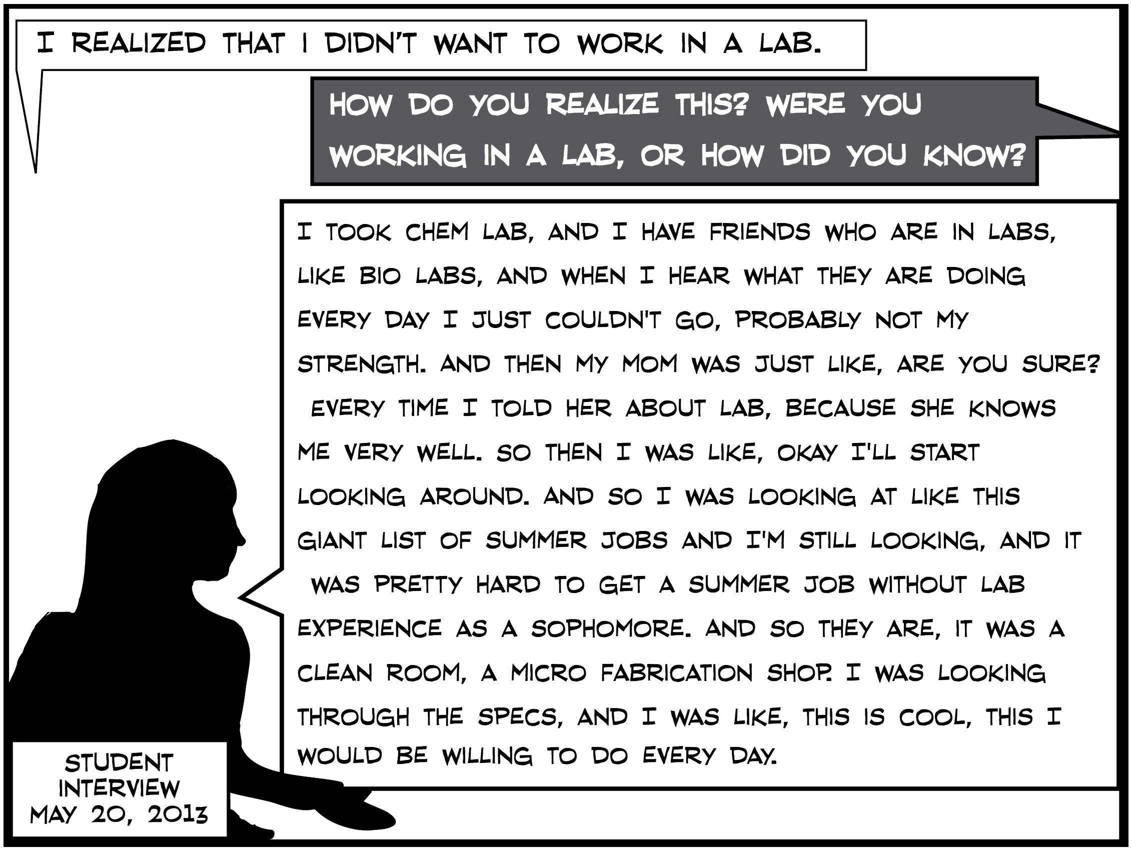

Illustration 100 Interview with NanoEngineering student, May 20, 2013.

I asked her to clarify what specifically would be different with respect to lab work if she was not in a bioengineering-oriented lab. Were there specific kinds of things she would find in a bioengineering lab that she wouldn't find doing materials science? She replied, "Yeah, most of the everyday kind of repetition. I've got friends [who] worked in labs like this. It's mostly just every day trial and error, and I'm not sure I have the patience for that." In trying to find working conditions that would be less repetitive and more interesting to her, she identified another focus that would align with different kinds of working conditions. Still, as she notes, it was not easy to find an internship without having the requisite lab experience.

For less savvy students, it can be difficult to make the kind of decision the above student made. That is because often internships and job descriptions do not use the words “nanotechnology” or “nanoengineering,” and there isn’t a formal part of the curriculum that helps students to identify appropriate jobs. If a student does not have laboratory experience or a close mentoring relationship with a professor, she may not have the resources to assess the fit between her education and the job descriptions she is searching, much less know how to frame a cover letter in a way that articulates her fit. One of the most common anxieties I heard from students stemmed from not finding jobs that invoke nano specifically, combined with a sense that the breadth of the nanoengineering curriculum may not trump the depth of the more traditional curricula their friends in other engineering majors are exposed to. This anxiety and the most common critique I heard from students—that the curriculum is too theoretical—are both suggestive to me of concerns that are grounded in a lack of laboratory experience.

The competition students face and the class dimension that is part of it (which may also intersect with race and gender dimensions) which affords some students more opportunity than others supports a state that “features winners and losers, not equal treatment or equal protection.”[22] While inequality and unequal protection are hardly new features of democratic life in the United States, Brown’s argument refers to a shift in the ideals and principles that form the democratic imaginary and horizon. Moreover, the constitution of all entities as capitals competing to enhance capital destabilizes the basis

22. Ibid.

for collective identities, for example, between workers *as* labor. This is a point that I will return to.

While risk-taking is not elaborated upon in the dean's comments, it might be understood not only in terms of venture capital and start-ups but also the on-going risk of working as human capital. Brown highlights the ways in which human capital is always in a state of precarity:

> We are human capital not just for ourselves, but also for the firm, state, or postnational constellation of which we are members. Thus, even as we are tasked with being responsible for ourselves in a competitive world of other human capitals, insofar as we are human capital *for* firms or states concerned with their own competitive positioning, we have no guarantee of security, protection, or even survival. A subject construed and constructed as human capital both for itself and for a firm or state is at persistent risk of failure, redundancy and abandonment through no doing of its own, regardless of how savvy and responsible it is. Fiscal crises, downsizing, outsourcing, furloughs—all these and more can jeopardize us, even when we have been savvy and responsible investors and entrepreneurs…. Human capitals do not have the standing of Kantian individuals, ends in themselves, intrinsically valuable.[23]

What Brown is highlighting is that the individual constituted as human capital is absolutely vulnerable, occupying an atomistic position that cannot count on firm, state, or even the solidarity of organized labor for insurance against destruction. This is the ultimate risk-taking.

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23. Ibid., 37-8.

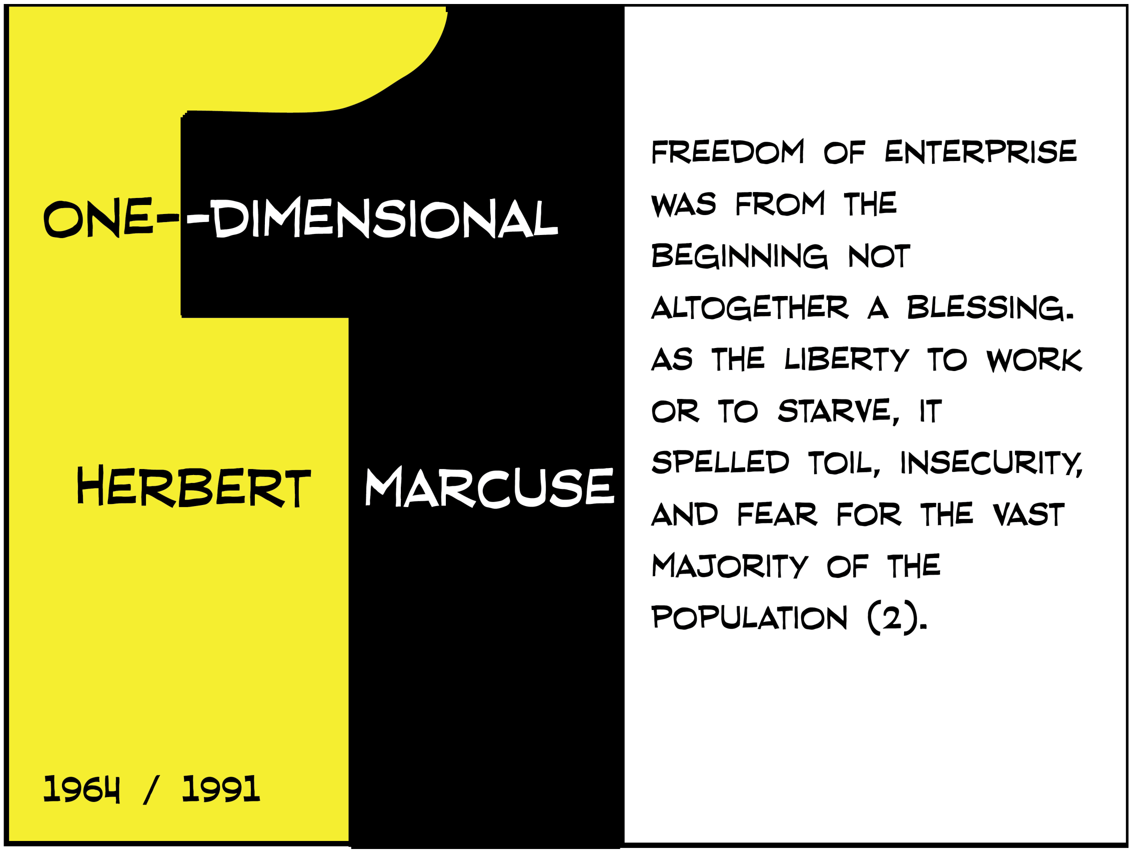

Illustration 101 Marcuse on precarity. Brown is not the first to discuss the precarity of the worker. Marcuse discussed the ways that "freedom of enterprise" constituted a state of precarity for the worker: "Freedom of enterprise was from the beginning not altogether a blessing. As the liberty to work or to starve, it spelled toil, insecurity, and fear for the vast majority of the population."[24]

And this precarity is intimately linked to Brown's key insight: capital has no minimum value, no baseline below which some other form of valuation kicks in. Moreover, the factors that contribute to a person's capital are not entirely within that person's control. To be human capital does not just entail a willingness to take risks; rather, it is a mode of always and necessarily being at risk. Having an entrepreneurial spirit may entail becoming an entrepreneur of one self but not necessarily of a company, much less a

24. Herbert Marcuse, *One Dimensional Man; Studies in the Ideology of Advanced Industrial Society*, Boston: Beacon Press, 1964, 2.

successful one. Conflating the at-risk condition of labor with the risk-taking of the entrepreneur, human capital must continually shoulder the risk of at-will employment.

In practice students don't necessarily recognize themselves as getting entrepreneurial training, in terms of concrete strategies for taking a product to market or starting a company—and this is more or less true depending on the student's individual

Illustration 102 Emily: Do you feel like through your four years here have you learned much about being entrepreneurial or about innovation? Student: I don't think so. And I've been here five years, this is my fifth year. But I don't think, I would say no to that.

experience in faculty labs, internships, and other innovation-related programs in the school. Yet they are initiated into a culture that holds entrepreneurial innovation as central to the promises and practices of nanoengineering. When they are welcomed to the university, the engineering school, and nanoengineering, students are introduced to the positive valence of entrepreneurialism, where the “entrepreneurial spirit” will give them this competitive advantage over other students and help them to translate their research into benefits for society. This positive valence is developed over the course of their four or five years in the undergraduate program—not necessarily in a linear, deliberate way, but it is a recurring theme that emerges in multiple ways during this time. Within the undergraduate major, the figure of the entrepreneurial-scientist-engineer-innovator (where each of the elements in this term also already connotes “for the benefit of society”) is produced through speeches, lectures and modeling as well as the lab participation, internships, and contests previously mentioned. By modeling, I refer to faculty modeling their own status as entrepreneurial-scientist-engineer-innovators in speeches, lectures, publications, lab work, and informal conversations. For example, such modeling occurs in an introductory nanoengineering class in which the professor introduces the department in part by indicating how commercially successful the faculty are:

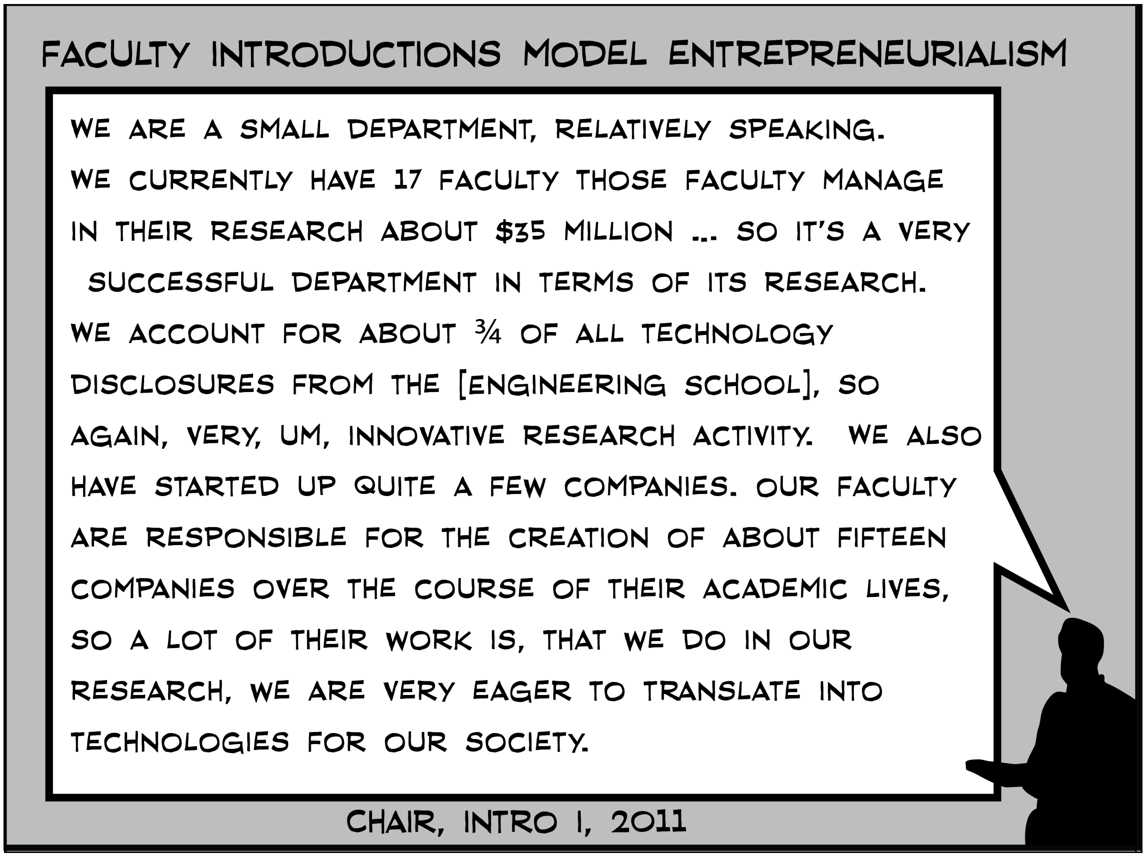

Illustration 103 Entrepreneurialism in the department. "We are a small department, relatively speaking. We currently have 17 faculty. Those faculty manage in their research about $35 million … so it's a very successful department in terms of its research. We account for about ¾ of all technology disclosures from the [Engineering School], so again, very , um, innovative research activity. We also have started up quite a few companies. Our faculty are responsible for the creation of about fifteen companies over the course of their academic lives, so a lot of their work is, that we do in our research, we are very eager to translate into technologies for our society."[25]

The success of their research is framed in terms of their ability to attract financial investment, key to capital accumulation. Brown identifies the ways in which a central aspect of the imperative to be entrepreneurial is the practice of attracting and maintaining investors—including traditional entities who invest financially, as suggested in this quote, as well as broader categories of investment such as the likes and followers of one's

25. NanoEngineering professor, NanoEngineering required course, 2011, transcribed by author.

electronic identities.[26] In the above quote, financial investment is an indicator of the successful entrepreneurialism of the faculty, and the capital enhancement of the faculty and department ultimately results in "technologies for our society." Note too that he describes creating companies as something the faculty do as part of their academic lives, not as something that occurs outside of or in addition to their academic identities. This makes sense within the logic of neoliberal rationality: if faculty are self-investing capital, and knowledge, thought, and training are essentially means for capital enhancement,[27] then there is no distinction to be drawn between the practices of the professor in a public university and those of an entrepreneur in a start-up company.

Within the classroom, faculty are introduced in terms of their entrepreneurial accomplishments—how many companies they may have started, how many patents they may have, and how marketable their research (intellectual capital) has been or promises to be:

> [Our] PI or Co-PI research projects on campus are connected to in excess of 30 million dollars of active research…So in terms of productivity, very very significant activity…*Our group also has started somewhere in the neighborhood of fifteen companies from the faculty itself, spinoffs. I've started a company* that actually I'm not even involved with anymore, they *commercially are selling products and generating revenue*….I'm actually involved in starting up another one right now. I've licensed another one of my technologies to a company in Michigan who is commercializing it. *[Another professor has] been responsible for the start up of eight companies of his own*…A professor who is part of our senior faculty was formerly the chief technology officer for [a nanotechnology company]. He…has…a year and a half ago, started another company called [a biotechnology company]. *One of his former graduate students is now the CEO* of it….

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26. Brown, *Undoing the Demos*, 33-4.

27. Ibid., 176-7.

> So…we are a department really committed to translational research. We want the stuff that we do to go out and be used by people. And so we have a very very strong focus on being able to take what we do and turn it into a real industry. So most of the faculty have been in academia with a leg in the private sector throughout their careers…. So we're very unique, down-to-earth, trying to get technology and science done in parallel.[28]

In the above quote, the chair of the department describes how professors, including himself, have started multiple companies and licensed technologies and "have been in academia with a leg in the private sector throughout their careers." And this mode of doing science and technology "in parallel" is valued as the way to make a "real industry," that is "unique, down-to-earth," and that creates technologies that will "be used by people." Yet the faculty are interesting models for entrepreneurialism in that, to the extent that they have tenure, the risks they take are somewhat qualified. To the extent that they start companies they are entrepreneurs in a traditional sense, not just entrepreneurial faculty. A key factor in their ability to achieve entrepreneurship—and particularly entrepreneurship with the fall back of a tenure-track faculty position—is the fact that they have a Ph.D. This is explicitly not what the majority of the undergraduate students are expected to have; the chair of the department has been clear that the industry needs bachelors degrees. The model before them, then, is a model of a faculty-entrepreneur, a position that most will not and indeed should not achieve if they become the bachelor degrees that will enable the industry, as the chair has indicated. Nevertheless, through these faculty introductions students can begin to see themselves as entrepreneurial

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28. Chair lecturing students in Intro I, 2011, observed and transcribed by the author, emphasis added.

nanoengineers, their future work in terms of patentable products, and the public as consumers who will buy their products. They can begin to see the market as the mechanism of translation that affords the possibility of benefitting society (I'll discuss translation in more depth in Chapter 6). And, importantly, they can begin to align their dreams, motivations, and ultimately their labor with the needs and aspirations of industry.

Entrepreneurialism as a mode of doing science and engineering in order to translate research is seen to some extent as being dictated by the political economy of science and engineering in the 21st century. That is, it is a necessity of the "real world" often invoked as a matter of pragmatics and pride for the engineer. As the chair indicated above, "…we're very unique, down-to-earth, trying to get technology and science done in parallel."[29] Students I have interviewed appear to be adjusting to this reality, even when they are somewhat critical of it. While one student whom I asked about the meaning of entrepreneurialism indicated some discomfort with it, he acknowledged it was just the way it works:

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29. NanoEngineering chair, NanoEngineering required course, 2011.

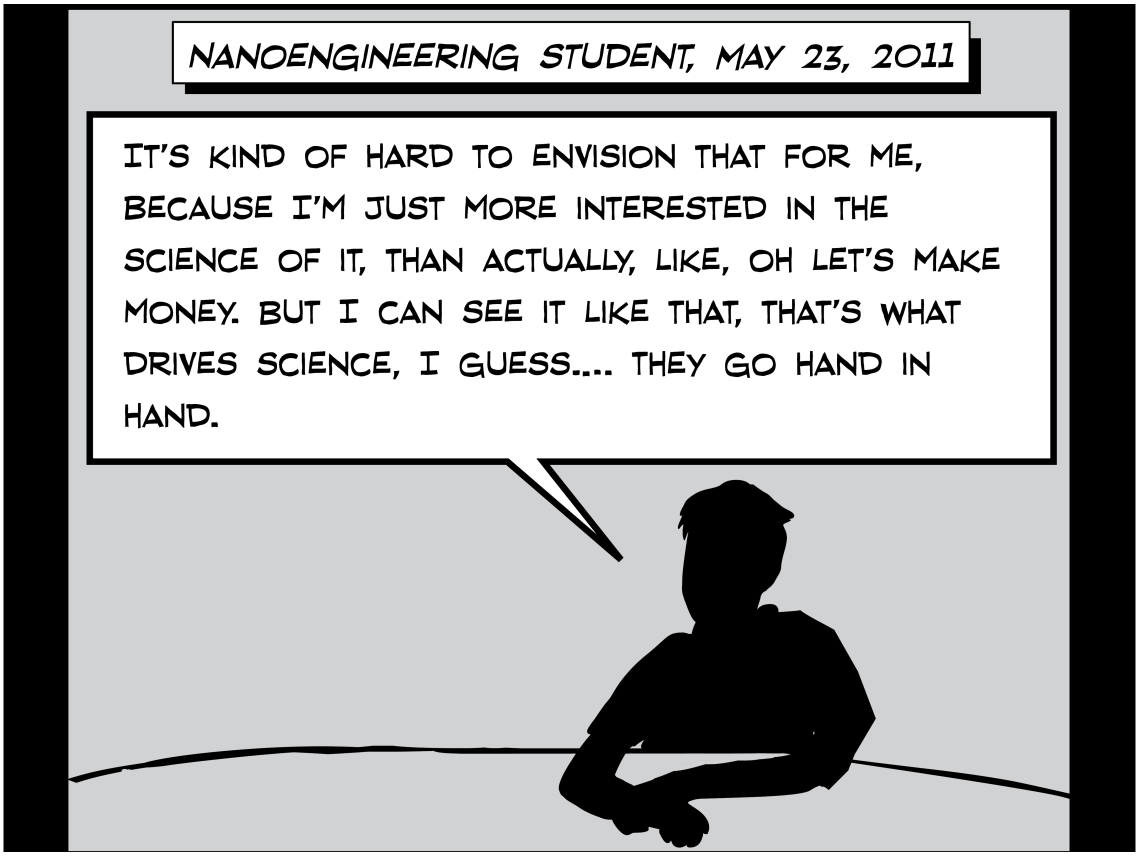

Illustration 104 Interview with NanoEngineering student. ""It's kind of hard to envision that for me, because I'm just more interested in the science of it, than actually, like, oh let's make money. But I can see it like that, that's what drives science, I guess…. They go hand in hand."[30]

Another student addressed the question of entrepreneurialism in a way that is more aligned with the positive valence articulated in the school:

30. Interview with NanoEngineering student, May 23, 2011, transcribed by author.

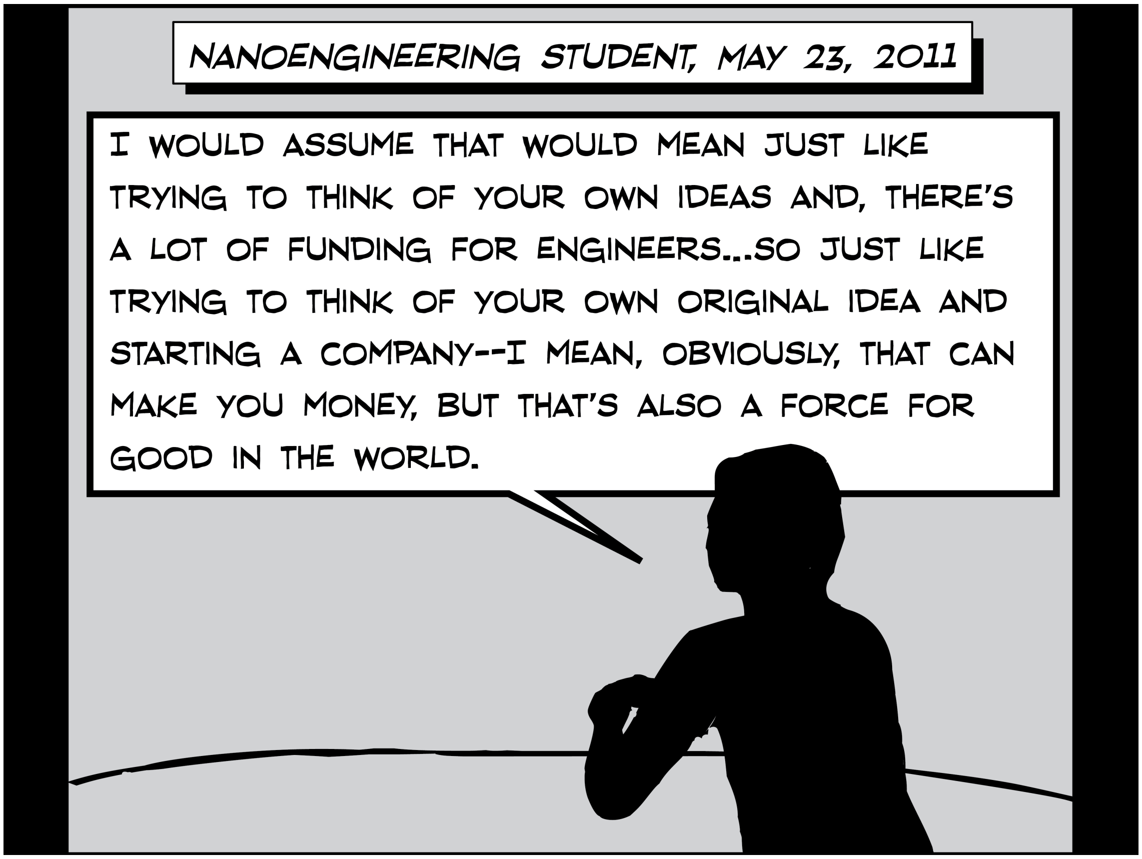

Illustration 105 Interview with NanoEngineering student. ""I would assume that would mean just like trying to think of your own ideas and, there's a lot of funding for engineers…so just like trying to think of your own original idea and starting a company—I mean, obviously, that can make you money, but that's also a force for good in the world."[31]

Here, while there is an acknowledgement that entrepreneurialism can make money, the emphasis is on having ideas, being original, and from there starting a company as a way to do good in the world. The good of the nanoengineering identity stems not only from the nano dreams of technological progress and saving lives, but through entrepreneurialism itself. This student articulates the dominant ideology that contributing to the public good occurs through private means, and models the practice of considering

31. Interview with (a different) NanoEngineering student, May 23, 2011.

world-building through market-based technological innovation. Another student's response suggests more ambivalence, as well as reconciliation:

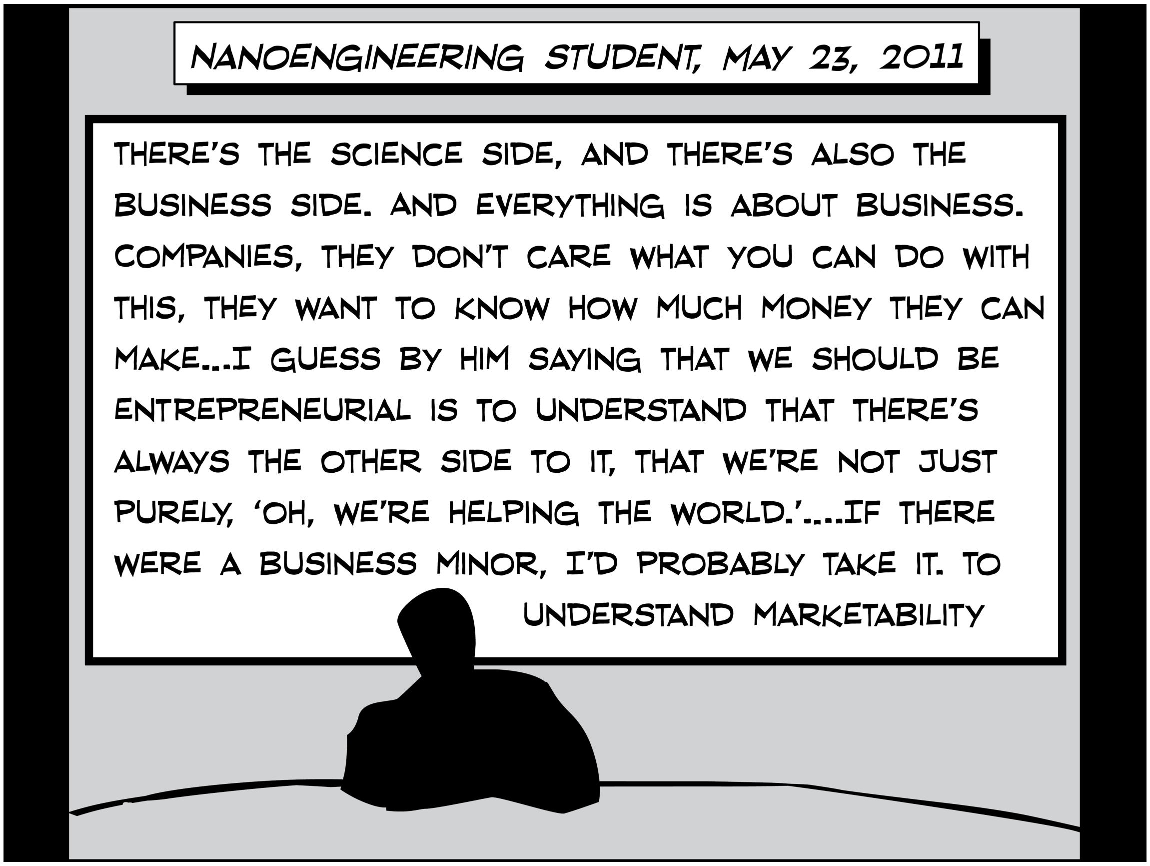

Illustration 106 Interview with NanoEngineering student. "There's the science side, and there's also the business side. And everything is about business. Companies, they don't care what you can do with this, they want to know how much money they can make…I guess by him saying that we should be entrepreneurial is to understand that there's always the other side to it, that we're not just purely, 'oh, we're helping the world.'….If there were a business minor, I'd probably take it. To understand marketability."[32]

The student distinguishes between science and helping the world on the one hand and business and making money on the other while at the same time recognizing that they are inseparable, and that to be successful, it is necessary to understand marketability. Faculty

32. Interview with (a different) NanoEngineering student, May 23, 2011.

introductions serve as one way through which students learn to see the market as necessary, not just desirable, for benefitting humanity through nanoengineering.

Finally, students—even as undergraduates—can start a company, particularly with the help of the Moxie Center, "a business incubator offering aspiring students the opportunity to become entrepreneurs."[33] It was established at the Jacobs School in 2012, with the following mission: "To motivate, educate, and mentor students to 'Dream, Design, Develop' their engineering ideas into commercial products" and "To add entrepreneurial practice to the undergraduate engineering program."[34]

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33. http://www.jacobsschool.ucsd.edu/moxiecenter/moxiecontent/faqs.html, accessed 06/29/2015.

34. The Moxie Center closed in the summer of 2015, and activities are continuing in other forms: "Without further philanthropic support to fund its operations, the Moxie Center officially closed on June 30, 2015, and its student teams have now transitioned into The Basement, a new student incubator space managed by Alumni and Community Engagement. Moxie Center Executive Director Jay Kunin, PhD, will continue to teach entrepreneurship and commercialization classes as a Lecturer in the Jacobs School of Engineering and in the von Liebig Entrepreneurism Center" (http://jacobsschool.ucsd.edu/news/news_releases/release.sfe?id=1775, accessed February 22, 2016). Other avenues for accessing opportunities in entrepreneurship are listed here:

"The UC San Diego entrepreneurship ecosystem includes the following:

*Von Liebig Entrepreneurism Center

entrepreneurship classes

entrepreneurship mentoring

* Innovation Corps (I-Corps) at UC San Diego (funded by the NSF and administered by the von Liebig Entrepreneurism Center). Read a story about the NSF I-Corps program at the on Liebig Entrepreneurism Center.

*Gordon Engineering Leadership Center at the Jacobs School of Engineering

The Gordon Center offers a novel, end-to-end set of leadership and training curricula for students at the high school, undergraduate and graduate levels, as well as for professionals working in technology fields.

*The Basement at UC San Diego In February 2015, UC San Diego opened The Basement, a co-working space for all UC San Diego students. The Basement serves as a resource and meeting place for entrepreneurial students from across all of UC San Diego.

*UC San Diego Entrepreneurship and Innovation Minor

administered by the UC San Diego Rady School of Management

open to engineering undergraduates (and all other UC San Diego undergraduates)

*The Triton Fund

venture capital focused on innovations coming out of UC San Diego

*UC San Diego Entrepreneur Challenge

student-run organization that organizes entrepreneurship events and competitions throughout each academic year. Each year's events culminate in high-profile business plan

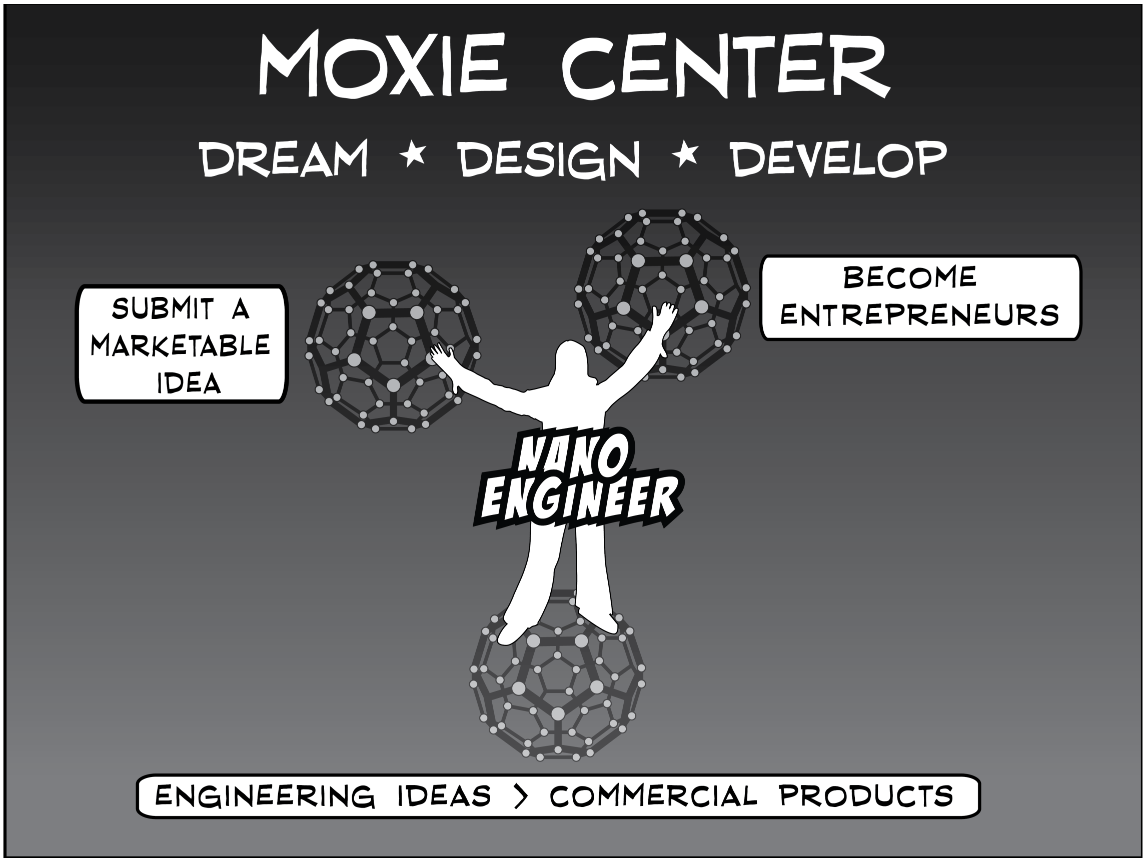

Illustration 107 Moxie Center.

Students can submit a "marketable idea," and if selected to join the incubator, they will be assisted with forming a team, developing a business plan and budget, obtaining mentorship from entrepreneurs, and prototyping. Through this process they can become an entrepreneur, using their marketable idea to produce intellectual capital while simultaneously producing themselves as human capital.

The goal of the engineering school to produce human capital is most visibly manifest in the nanoengineering program in its emphasis on entrepreneurialism. Notably this emphasis is less apparent, however, in the National Academies Report *The Engineer*

competitions." (http://jacobsschool.ucsd.edu/news/news_releases/release.sfe?id=1775, accessed February 22, 2016).

of 2020 (hereafter just *2020*), which the department used as a guide for creating the curriculum. The report situates engineering within the framework of progress and societal benefit to be sure, but gives little explicit attention to entrepreneurialism. In it, benefit and progress are woven together into a statement of ethos for engineering :

> Without engineers working both in technical endeavors and as leaders…progress would stagnate. Engineering offers men and women an unparalleled opportunity to experience the joy of improving the quality of life for humankind through development of engineering solutions to societal problems.[35]

It goes on to speak of the ideal engineer as having "…the ingenuity of Lillian Gilbreth, the problem-solving capabilities of Gordon Moore, the scientific insight of Albert Einstein, the creativity of Pablo Picasso, the determination of the Wright brothers, the leadership abilities of Bill Gates…"[36] While some of these figures could be said to have had what the dean called an "entrepreneurial spirit" there is no explicit discussion here of teaching students how to be entrepreneurial, or why entrepreneurialism would be an important attitude or skillset for the engineer of 2020. *2020* is a proposal for what engineering education should do in service of the nation and the engineering profession in the 21st century. In it, societal problems are to be confronted with engineering solutions. While engineering solutions are implicitly figured as market-based solutions, *2020* also sees contributions to the public good that are not necessarily market-based. It calls for the engineer to be actively involved in matters of public policy, governance, and other aspects of civic life, exercising leadership in all areas of society based on the notion

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35. Engineering, National Academy of. *The Engineer of 2020: Visions of Engineering in the New Century*. National Academies Press, 2004, 48.

36. Ibid., 57.

that society is fundamentally technological. While this call to public leadership may have more to do with creating a favorable environment for these market-based solutions, it is nevertheless an articulation of the engineer as a political member of the polis that is not directly taken up in the department. Instead, the public good is primarily articulated in terms of societal benefit achieved through nanotechnologies translated via the market.

The entrepreneurial spirit students are supposed to attain articulates this ethos of engineering for societal benefit, public good, and progress, through the practices of competing, taking risks, identifying market opportunities, obtaining patents, and starting companies. Learning to identify with the figure of the entrepreneur, nanoengineering students are encouraged to pursue their nano dreams, like the faculty entrepreneurs who mentor them. I have already suggested two reasons to be cautious: first, most students will not become faculty or entrepreneurs of companies, and second, human capital is always in a state of precarity. Now I want to step back and ask, what does it mean for the university to *want* to produce human capital (bracketing the question of whether it is succeeding in this)? Does this present anything new or different from what the university was attempting to do when Clark Kerr spoke of the knowledge industry, or even before that?

Producing Neoliberal Citizenship in the University

The University as Mediating Institution

The purpose of the engineering school, and by extension the university as an institution, is made explicit in the dean's comments: it is to produce capital—human and intellectual varieties. Indeed, knowledge (that counts) is capital according to this perspective, and a four-year education in this public university and particularly in the engineering school should train students not only to understand and value knowledge as capital, but to understand and value themselves as capital, too. But why is this the institution's goal and what are the politics of this? Is this something new? I argue that the university is an institution that necessarily mediates between state, industry, and citizen in determining what kind of graduate it should produce. This is not a passive act—the university actively communicates what kind of graduate it should produce as well. But its imperatives to be relevant to state, industry, and citizen, in terms of its educational function demand that it dynamically anticipate and respond to the perceived needs of each, to produce the graduate that is in demand, as it were. And the graduate that is widely in demand by each of these entities, including the university, is one who is also (explicitly or implicitly) the subject of human capital.

I take the dean's statements as necessarily political statements that reflect not only his personal politics but the politics of the institution for which he speaks (particularly since his language reflects the school's vision statement). Educational researcher Michael Apple reminds us that "education is not a neutral enterprise"[37] and that "the structuring of knowledge and symbol in our educational institutions is intimately related to the principles of social and cultural control in a society."[38] By this he suggests that the educational institution is a political apparatus that produces knowledge and also articulates what counts as knowledge, and how and by whom knowledge should be

37. Michael W. Apple, *Ideology and Curriculum*, 3rd ed. New York: Routledge Falmer, 2004, 1.

38. Ibid., 579.

characterized, transmitted, and valued. By "social and cultural control," Apple is indicating the power of hegemonic ideology, as articulated through Raymond Williams and Antonio Gramsci, that which is "vested in the constitutive principles, codes, and especially the commonsense consciousness and practices underlying our lives."[39] That it is apparently unremarkable that the dean would frame knowledge and students as capital and as products suggests that this framing is commonsense. Moreover, the dean legitimates the categories—intellectual capital and human capital—and ideologies of human capital theory, which include an emphasis on the marketability of research, technology, and graduating students alike. These are ideologies that are grounded in neoliberal rationality. As Apple suggests (via Gramsci), ideological hegemony emerges not just from categories and structures of feeling that are determined by the economic mode of production, but also through the activities of a society's intellectuals who legitimate these categories and make these ideologies appear neutral.[40] The dean's welcome address is an instance of the latter.

I want to note, however, that I do not invoke the term ideology to suggest that the dean is somehow duping these college students and their parents, or that by virtue of constituting an ideology the principles stated are any less real. Indeed, this chapter is an attempt to show how such ideologies are materialized in a department and university. Moreover, to understand oneself as human capital may be felt as empowering. As human capital, students are making a self-investment by attending this university and this

39. Ibid., 4.

40. Ibid., 772.

investment may produce positive returns in terms of dollars spent on education and income following graduation. In the introduction to this chapter, I referenced Foucault's analysis of *homo oeconomicus* under neoliberal theory which shows that "the worker is not present in the economic analysis as an object—the object of supply and demand in the form of labor power—but as an active economic subject."[41] Active economic subjects are subjects that are ostensibly able to make choices and exercise freedom regarding their investment decisions. If to be human capital is in part to understand oneself as an active economic subject, freely making economic choices, it may be regarded as empowering, even exciting. Nevertheless, I want to take a closer look at human capital theory as an ideology that is being articulated by the university through its emphasis on human and intellectual capital and entrepreneurialism.

41. Foucault, *The Birth of Biopolitics*, 223.

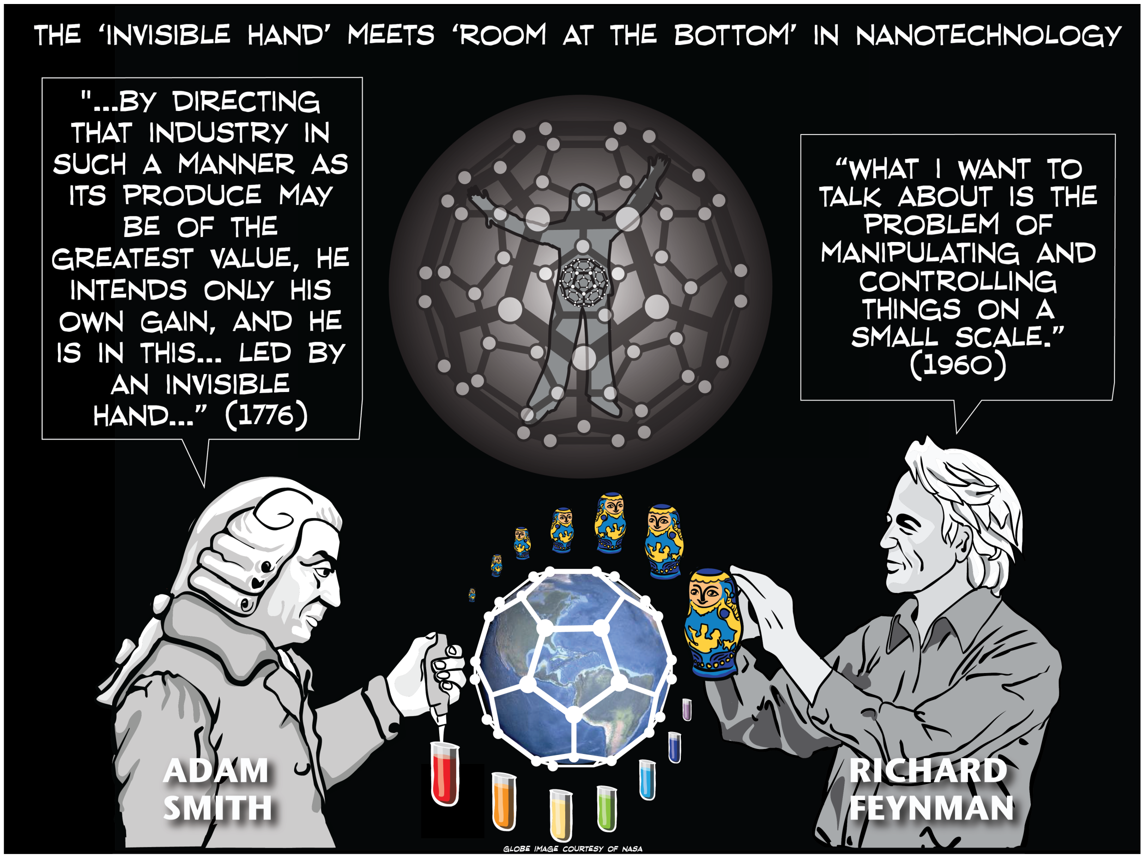

Illustration 108 Smith meets Feynman.

On the one hand, the University of California contains multiple politics that cannot be reduced to neoliberalism. On the other hand, neoliberalism as a signifier of the modes of rationality and the vectors of power that constitute the university as a firm increasingly oriented toward producing intellectual and human capital is one that must be engaged if also unpacked. The term "neoliberalism" may be overused and often misused, but that is insufficient reason to avoid it for two reasons: it indicates a set of ideologies (however historically and geographically contingent) that are currently dominant and interrelated in the United States and that have a particular history and trajectory; and it is central to understanding both technoscientific knowledge production and the university in the United States generally, and my site of nanoengineering within the University of California specifically. The fact that human capital theory—first proposed by key proponents of the Chicago school of economics who were at the same time expanding and developing neoliberal thought—is enshrined in the vision statement of the engineering school should be one indicator of this. I have already begun to connect my analysis of entrepreneurialism in the undergraduate program to neoliberal rationality, drawing primarily on Wendy Brown's insights into the ways that all entities according to neoliberal rationality are constituted primarily as capitals engaged in capital accumulation. Neoliberal rationality is a political rationality, "the condition of possibility and legitimacy of its instruments, the field of normative reason from which instruments and techniques…are forged."[42] It is this rationality that enables and supports expanding economization of all spheres, and this economization presupposes a specific, historically contingent version of economic life as "a market of competing capital entities, large and small."[43] In Chapter 3, I also drew on Philip Mirowski's analysis of neoliberal thought,

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42. Brown, *Undoing the Demos*, 121.

43. Ibid., 83; Elizabeth Popp Berman, "Not Just Neoliberalism: Economization in Us Science and Technology Policy," *Science, Technology & Human Values* 39, no. 3 (2013): 397-431; Mirowski, *Science-Mart*.

Berman argues that neoliberalism and economization are compatible, but not the same. Through an analysis of science policy, she argues that some science policies that have been attributed to neoliberalism are actually just reflecting economization. However, I take issue with her distinction between neoliberalism and economization on several grounds. First, I think her definition of neoliberalism is too narrow—the "idealization of the market and a belief that the main role of government should be to create and uphold markets" (399)—and I was surprised that she chose to rely most on David Harvey's version of neoliberalism, which has largely been discredited by scholars in STS more recently, such as Philip Mirowski. Second, I would argue building on Brown that neoliberal rationality (which might be a broader framing than Berman's "neoliberal political agenda" (400)) is precisely what enables the expansion of economization, and that economization specifically refers to particular (neoliberal) understandings of economic life. Third, while Berman's approach to analyzing neoliberalism versus economization in science policy relies on finding precise causal mechanisms, I think analyses of neoliberal rationality more broadly highlighting the ways in which neoliberalism posits the market as nature's ideal information processor, and as key to solving any problem, even one caused by the market.[44]

There are several additional elements of Mirowski's analysis that are useful for thinking about the university and the production of human capital. In *Science Mart*, Mirowski argues that there is a flattening of distinctiveness between university, citizen, state, and industry, a point that resonates with Brown's claim that each is reduced to capital.[45] It should be noted that this does not mean there is a flattening of distinctiveness between individuals. Instead, the drive toward personalization is premised on the distinctiveness of the individual biologically and otherwise; this individualism is in line with Brown's emphasis on competition as the central principle at work, as opposed to

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may not always search for or find precise causal mechanisms (between neoliberal rationality and a particular political practice or outcome, which may have complicated sets of conditions enabling them), and that this does not then mean that neoliberal rationality is not informing that political practice or outcome. Finally, one of her key distinctions between neoliberalism and economization with respect to science policy is that some policies have been "justified in terms of their effects on the economy" but not necessarily achieved through market means (404). Her argument hinges on the notion that policies relying on direct government interventions in creating a science base—such as the NSF's Small Business Innovation Research program—are "clearly not neoliberal" because they involved a direct government role, or because they were supported by progressives and opposed by neoliberals. On the latter point, people across the political spectrum may not be "neoliberals" yet nevertheless operate according to neoliberal rationality. But regarding a direct government role in creating a science base, a broader interpretation of neoliberal theory accounts for this in that government investment in the infrastructure for innovation is considered necessary to enabling innovation. Mirowski points out, quoting the economist Paul Nightingale, that, "'The justification for the public funding of science is not based on unquantifiable, abstract theory or market failure arguments about the provision of public goods. It instead revolves around the empirical requirement for the infrastructure needed to produce technology and all markets to work'" (82). That is, government funding of research, when justified in terms of economic goals, is part of the economization that is central to neoliberal rationality per Brown and is part of creating and maintaining markets. Berman points out that neoliberalism and economization are compatible, and I agree with that, however I think the distinctions she draws assumes that when there are elements involved that are not directly caused by neoliberalism, then they cannot be attributed to neoliberalism and must therefore be attributed to the related project of economization. I would suggest instead that while many facets of science policy may not be reducible to neoliberalism, economization is itself part of neoliberal rationality.

44. Mirowski, *Science-Mart*.

45. Ibid.

exchange. Mirowski also argues that the corporatization of the university is a prelude to the state's withdrawal from providing education.

Illustration 109 Mirowski on the corporatization of the university. "…Universities are being expected to become more like corporations—to regard their products as 'information' and 'human capital,' they treat their students more like customers—as a prelude for the state to withdraw from all responsibility for the provision of education."[46]

Again, this is a point that resonates with Brown's claim that with neoliberal rationality the state becomes a private actor and public goods are eliminated. But what may be more interesting in Mirowski's argument is his emphasis on information. If the market is ultimately an information processor, in the logic of neoliberalism, then it stands to reason that what the market needs is information, or data. Capital is wealth that, in theory, can be

46. Ibid., 23.

quantified. Human capital is measured in terms of incomes and earning potential. That is, capitalization of intellectual and human products is a way of datafying the outputs of the university in terms of growth. While the corporatization of the university is not new, and the state's involvement in providing education has often been precarious, the shift to producing intellectual and human capital signals not just corporatization but also the capital valuation of its products, whether intellectual or human. Even as human capital indicates the *corporalization* of capital in the human body, it simultaneously provides a *decorporalized* unit of measurement to stand in for that body which can readily be processed by the market. To pick up on my previous chapter, the university renders itself the set of conditions within which the self-assembly of intellectual and human capitals occurs, capitals that can be marketized.

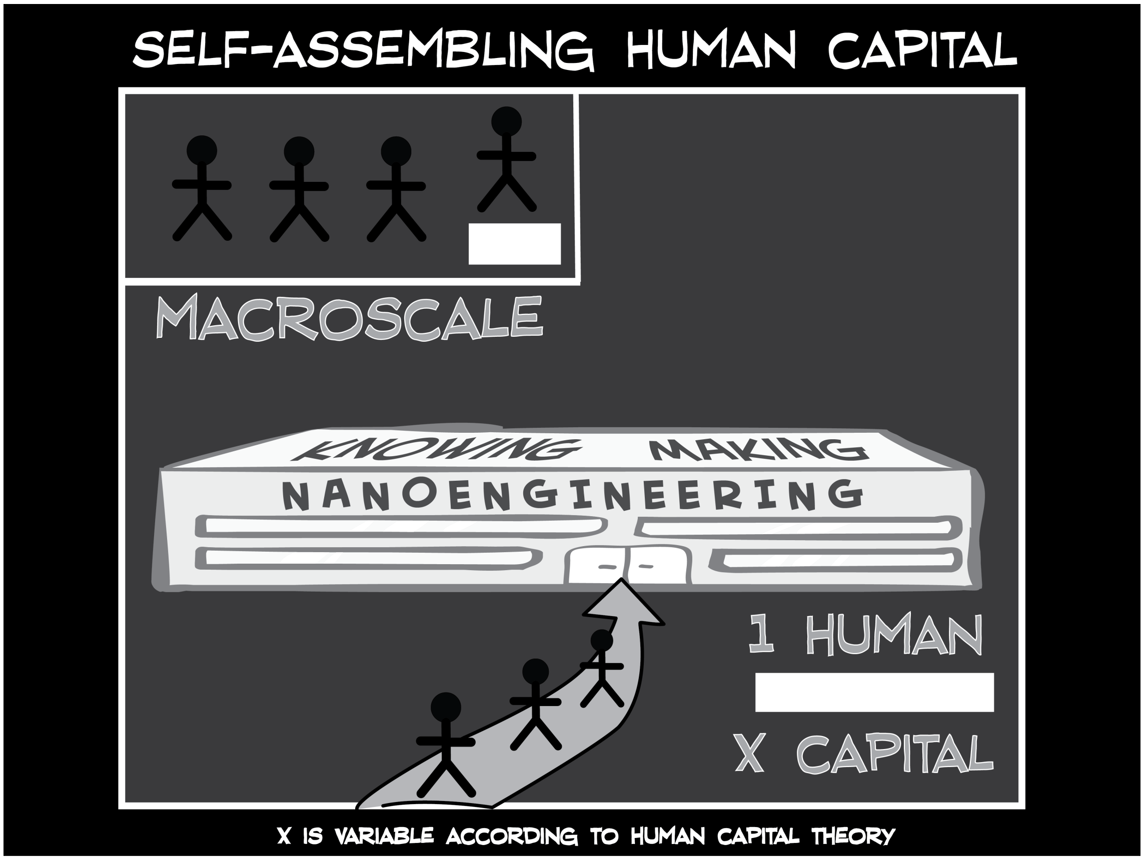

Illustration 110 Self-assembling human capital.

The individual of the contemporary university is not the Kantian individual of reason, or the German Idealist's citizen of national culture who was the object of the 19th century German university instituted by Wilhelm von Humboldt,[47] or even human capital's immediate predecessor, the human resource produced by the late 20th century university.[48] Human resources still need to be taken care of. Human resources need training, management, benefits. Human capital, on the other hand, is liberated from the

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47. Bill Readings, *The University in Ruins*, Cambridge, Mass.: Harvard University Press, 1996.

48. Ibid. Readings argues that Kant defined the modern university around the principle of reason, and that the German Idealists replaced the principle of reason with that of culture. After 1968, culture was replaced with the concept of excellence—unique from the other two in that excellence has no referent.

corporation as well as the state, which is to say, it is entirely responsible for itself and its continual accumulation of capital. Yet, as I argued in the previous chapter, autonomy in the logic of self-assembly can only be understood in fairly narrow terms because the conditions of possibility for such assembly are limited. Moreover, as Brown points out, the autonomous subject of both liberalism and neoliberalism is a masculinist subject that "fails to feature the conduct that binds families and societies and is also falsely autonomous—shorn of needs and dependencies."[49] The autonomous subject depends, in fact, on labor and structural support that is rendered invisible by its theorists.

But again, does this signal a substantive change for the university? Christopher Newfield documents the ways in which the research university in particular was indeed "constituted by business agendas from its inception"[50] and notes that while complaints about the university's corporatization may have spiked in the 1990s, the conditions were hardly new; as early as 1909 one alumnus of Harvard complained that "'the men who control Harvard today are very little else than business men, running a large department store which dispenses education to the millions.'"[51] Its devotion to economic growth is, according to Newfield, one of the two distinctive features of the research university as it emerged in the United States following the Morrill Act of 1862.[52] Along with its obsession with economic growth was an early embrace of quantitative methods for

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49. Brown, *Undoing the Demos*, 103.

50. Christopher Newfield, *Ivy and Industry : Business and the Making of the American University, 1880-1980*, Durham, N.C.: Duke University Press, 2003. 16.

51. Ibid., 15.

52. Ibid., 28. The Morrill Act supported the founding of public universities that taught agricultural and mechanical arts. The other distinctive feature, according to Newfield, is its lack of a core identity.

measuring academic success. While the University of California has had operational independence from the state legislature since 1879, that did not mean it was ever financially independent, and industry has continued funding university research throughout the 20th century.[53] Indeed, Newfield writes:

> Until massive federal support was established during World War II, the university's fiscal crises of the 1930s and 1990s were the norm rather than the exception. Modest stability required the support of external benefactors and patrons. Sometimes these external benefactors were religious denominations. Sometimes they were men of wealth.[54]

In the case of UC San Diego specifically, the campus essentially developed as an extension of the military, with San Diego's UC Division of War Research opening in 1941.[55] And its early funding also included industrial sources, such as early American Petroleum Institute funding to support the university's participation in searching for oil.[56]

Therefore Christopher Loss' argument—that the public university in the United States has always mediated between state and citizen to produce the citizens the state says it needs—should be qualified to account for this history with industry.[57] Loss shows that the public university of the 1930s and 40s, for example, was geared toward producing citizens who would be prepared to accept the large bureaucratic state of the New Deal era

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53. Ibid., 37.

54. Ibid., 24-5.

55. Nancy Scott Anderson, and University of California San Diego, *An Improbable Venture : A History of the University of California, San Diego*, La Jolla, Calif.: UCSD Press, 1993, 24.

56. Ibid., 25.

57. Christopher P. Loss, *Between Citizens and the State : The Politics of American Higher Education in the 20th Century*, Politics and Society in Twentieth-Century America, Princeton, N.J.: Princeton University Press, 2012.

and to engage in democracy as political members of the polis.[58] But the university has also at least since the early 19th century—when universities began to incorporate scientific and technical training into the curriculum—mediated between citizen, state, *and* industry, addressing the needs of both state and industry in the production of its graduates. As David Noble outlines, early attempts to introduce technical education to classical colleges in the early 19th century were met with some resistance.[59] However with a rise in canal building there was also an increase in demand for such education, and private contributions for new schools and new curricula within existing schools—such as Stephen van Rensselaer's contribution to the establishment of the Rensselaer School in 1823, and mill owner Abbott Lawrence's contribution to Harvard to establish the Lawrence School for scientific studies—established technical education as the means through which the university began to respond to industry's demands.[60] Yet the tensions that marked these early moments of mutual response began to ease after the 1862 Morrill Act.[61] The Morrill Act, after all, directly supported what was considered practical education. And indeed by the late 19th century, many began to question the value at all of a liberal arts education, to the extent that the outgoing UC president Daniel Coit Gilman

58. Ibid.

59. David F. Noble, *America by Design : Science, Technology, and the Rise of Corporate Capitalism*, 1st ed. New York: Knopf, 1977, 20-24.

60. Ibid.

61. Ibid., 24.

defensively argued in 1885 that the pursuit of fundamental research—not wealth—was the central motivating factor creating material progress.[62]

If Loss' argument is modified, then, to say that the university mediates between state, industry, and citizen, to answer the demands of both state and industry, then the production of citizens prepared to be administered to by the New Deal state is continuous with the late 19[th]th century research university's production of citizens prepared for the industrial system.

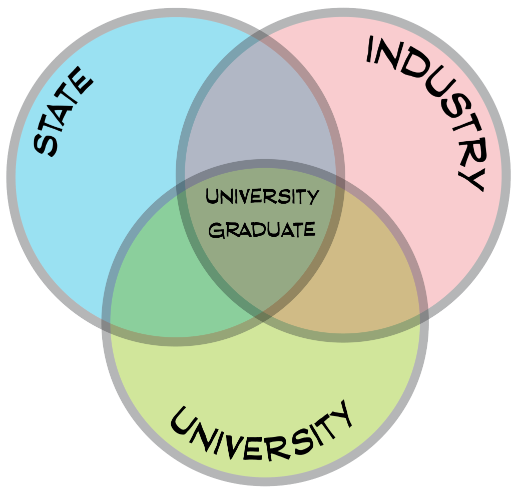

Illustration 111 University, state, industry, university graduate.

Newfield argues that "the research university was a central component of the rising industrial system…. It created managers, people who had the independence to manage others and the malleability to be managed themselves."[63] That is to say, the university has

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62. Newfield, *Ivy and Industry*, 42.

63. Ibid., 16.

necessarily been attentive to what skills and values are expected of its graduates by state and industry both. In an era of industrialization, the university produced managers. In an era of a growing bureaucratic state, the university produced citizens prepared to be administered to. Yet while universities may have a long history of embracing business objectives and methods, they were never in fact business corporations.[64] They embraced growth, but they did not emphasize capital accumulation as such.

I suggest that the contemporary university continues the historical trend of mediation, producing the citizens that today are demanded by the neoliberal state and the industry interests it serves as well as by the neoliberal subject who wants a positive return on her investment in the form of an income-earning job that is good relative to any debt she incurs. What is unique to this moment is less the corporate influence on the university as much as the kind of citizen currently in demand by state, industry, and citizen.

64. Ibid., 32.

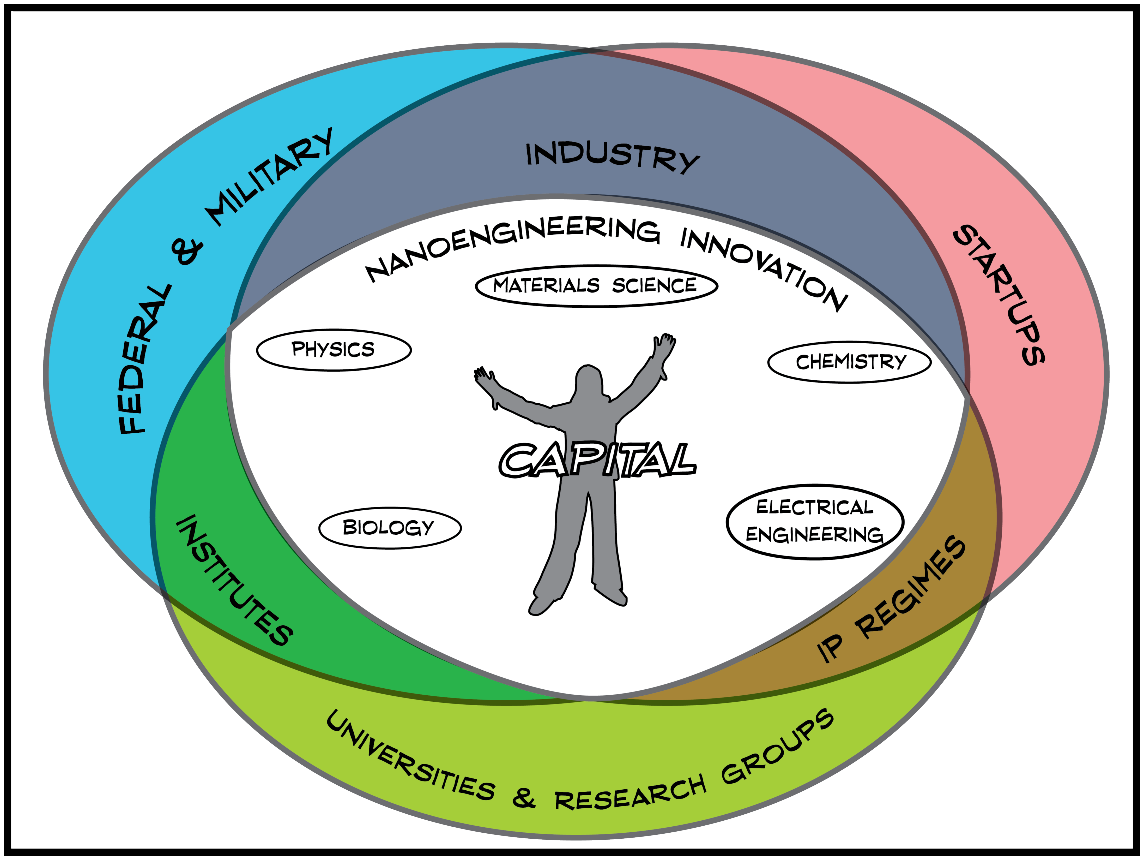

Illustration 112 University graduates as capital.

These are citizens who will be entrepreneurs of themselves[65] and operate as self-investing capital,[66] who understand the common good as secured through privatization, who will continually engage in training in order to sustain their capital in the face of permanent job insecurity, whose contribution to society is primarily constituted through their contribution to capital enhancement, and whose participation in the polity occurs through economic conduct. That is, these will be citizens who expect a state that exists to create

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65. Foucault, *The Birth of Biopolitics*, 226. Also see Aihwa Ong, *Neoliberalism as Exception: Mutations in Citizenship and Sovereignty*, Durham [N.C.]: Duke University Press, 2006.

66. Brown, *Undoing the Demos*.

and maintain markets—a neoliberal state—and who expect an individual (not collective) relationship to their employer that is always tenuous. I will discuss the implications of this momentarily.

The Mutual Articulation of the Ideal Graduate

When I say that the university mediates between state, industry, and citizen, I do not mean that it is a disinterested actor. Rather, it plays an active role in articulating what kind of graduate and citizen it should be producing. Let me concretize the previous section by demonstrating how such mutual articulation by university, state, and industry takes place.[67] This is not a simple, didactic, or uni-directional process; when state, industry, or university communicates about the desirable graduate, these communications are multi-vocal, already containing the traces of each other.[68] I will focus specifically on examining these communications in relation to the formation of this Department of NanoEngineering and its undergraduate major.[69] If the university's creation of this

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67. At this time, I do not have data to analyze communications coming from students, future students, or their parents.

68. James Wertsch, "The Multivoicedness of Meaning," In *Discourse Theory and Practice: A Reader*, edited by Margaret Wetherell, Stephanie Taylor and Simeon Yates, 222-35: Sage Publications, 2001.

69. Newfield, *Ivy and Industry*; Lave, Mirowski, and Randalls, "STS and Neoliberal Science".

Such communication can occur indirectly through policies (e.g., The Bayh-Dole Act) and (de)funding practices which push the university to corporatize and which then, through the economic imperatives of capital enhancement, encourage the capitalization of knowledge. Newfield calls this the "dependency thesis":

> Changes in the economic environment intensify the university's state of financial dependence, which boils down to a dependence on market revenues. Universities that license their inventions to business firms are dependent on market dynamics and on the firms that dominate markets. Administrators logically come to value business thinking, to think more like business people, and to invite business people to join and shape their work (Newfield, 18).

department and major is in some part anticipating and responding to the state and/or industry, are there traces of this in the department and major proposal? The answer is yes, at least insofar as the university wishes to position itself as constituting itself to meet state and industry needs. And these communications articulate the undergraduate curriculum in terms of producing an ideal workforce.

First, by establishing an interdisciplinary program aimed at addressing the specific intellectual and cultural challenges raised by nanotechnology, the department proposal aligns its mission with that of the state. By "intellectual challenge," the department refers to the ways in which nanotechnology cuts across disciplinary boundaries, and requires knowledge often in several different fields. By "cultural challenge," the department refers to the requirements of working in diverse interdisciplinary teams, including scientists and engineers, in order to develop nanotechnologies.[70] By establishing a nanoengineering department and educational program, the department situates itself as providing an institutional space and developing a curriculum that will produce nanoengineers who have grounding in this interdisciplinary knowledge and who will work in teams as part of their training. The Proposal says:

This means that the university's dependence on the market percolates through every aspect of the institution, which ultimately results in, among other things, conceptualizing its outputs in market terms, such as the production of intellectual and human capital. Certainly the rolling back of public funding since the height of the Cold War has made research agendas more dependent on industry sources and the need to commercialize knowledge (Lave et al., 59).

70. Sadik Esener, Michael Heller, Sungho Jin, Jan Talbot, and Kenneth Vecchio, "Proposal for the Creation of the Department of Nanoengineering (Ne) within the Irwin and Joan Jacobs School of Engineering at the University of California, San Diego," i-175, 2007, 3.

> Many National Science Foundation, National Nanotechnology Initiative, and National Academy of Engineering panels have discussed these "cultural" and "intellectual" challenges in nanotechnology, and all of these panels agree that this need for multi-disciplinary expertise must be addressed and solved….The NE Department is being proposed to address these technical, cultural, and intellectual challenges at UCSD. Many of the comments, visions, and suggestions of these national panels will guide its creation.[71]

Here, the proposal explicitly frames the department as a response to the call of the nation. The call does not occur as a singular directive—from the state to the university—rather, the state communicates through diverse means, and members of the university locate and justify their interests as a response to the state. The university in this case approves the department proposal, and a new department is established. Moreover, when the state communicates, its communications are already informed by the university. In this case, the reference to the National Academy of Engineering is later specified to refer to a specific set of reports on the education of engineers. The first part of this report—*2020*, which I previously referenced—was produced by a commission that included one of the founding members of this department. If this is a call and response, it is also a messy network of communications moving both directions.

The proposal also connects the establishment of the department to the interest—expressed in dollars—at both the federal and state levels in advancing nanotechnology. It says:

> There is great interest in advancing nanotechnology research and education at both the state and federal level. The federal government established the NNI—a federal multi-agency R&D program—in 2001 to coordinate the multi-agency efforts in nanoscale science, engineering, and

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71. Ibid., 3.

> technology; the 2001 budge was $464 million. The President's 2007 Budget provides over $1.2 billion for the NNI, bringing the total investment since the NNI was established to over $6.5 billion. The State of California recognizes that California needs to be a major participant in the nanotechnology revolution to preserve this technology leadership and its economic strength. A Blue Ribbon Task Force on Nanotechnology was commissioned by the state in December 2004 to assess the state of nanotechnology in California and to make recommendations for ways to make the industry a statewide success. The goals of the new NE Department are directly in line with federal and state nanotechnology initiatives.[72]

Here, evidence of increasing nanotechnology budgets since 2001 and of the state's economic hopes for a nanotechnology industry are invoked to produce the department as a logical materialization of the state's plans. The proposal also clearly ties the department's goals not only to science and engineering on the nanoscale, but to the "technology leadership" and "economic strength" necessary for a new industry. These justifications are not so different from the promises of the 19th century research university, to produce managers and to contribute to economic growth.

With respect to responding to industry, there are fourteen letters of support from corporations—twelve technology companies and two venture capital companies—included as an appendix to the proposal. Who is responding to whom is here even more ambiguous. On the one hand, the university frames itself as responding to industry in that the department answers a need expressed by industry as evidenced by these letters. On the other, industry responds to the university by supplying letters of support that are apparently in response to a solicitation by the Jacobs School of Engineering. Given the similarity between the letters, it is likely the school gave the companies a template for

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72. Ibid., 6.

their letters of support. In the letters, common features are as follows: the company acknowledges that it learned of the creation of this “innovative new department” through its affiliation with the Jacobs School Council of Advisors and sometimes also through the School’s Corporate Affiliates Program, it indicates that it would like to have an affiliated relationship with the new department, it claims that the department’s graduates “are likely to become leaders in this new field” and that they will be “vital [to the] continued revolution” in nanotechnology, that it is necessary to produce engineers trained in the unique aspects of the nanoscale, that the department is likely to “become an important source of [its] future employees,” and that the department will be important to the San Diego region in relation to nanotechnology.[73]

73. Ibid., Appendix 9.

Illustration 113 Corporate Affiliates Program.[74]

These letters situate the department as responding to the needs of industry (nationally and regionally) and as producing the future employees these companies want and need. At the same time they are a response of approval and endorsement by industry to those in the Jacobs School of Engineering attempting to create this department.

Neither the proposal nor the companies' letters use the term "human capital." If this is a mutual articulation of a particular kind of graduate, it is organized around a call for nanoengineers and the response of a nanoengineering department. But the

74. Modified image based on original image, original image and text come from: http://jacobsschool.ucsd.edu/external/external_cap/, accessed March 3, 2016. Author invokes fair use of original image.

nanoengineering department is articulated as an economic entity and situated as one that responds to national, state, and regional interests in economic growth through technological innovation. Central to the department's constitution as an economic entity is its production of future employees who will work in industry. These employees need to be highly skilled and entrepreneurial. The proposal states that the curriculum will, as one of its course-specific outcomes,

> Educate a new generation of scientists who can participate in, and indeed seed, new high-technology companies that will be the key to maintaining jobs, wealth and education infrastructures as nanotechnology results in a new industrial revolution.[75]

These are scientists who are expected to understand themselves as human capital. Yet, as I've already noted, they also need to be the "workforce" of the industry.

75. Esener et al., "Proposal for the Creation," 8.

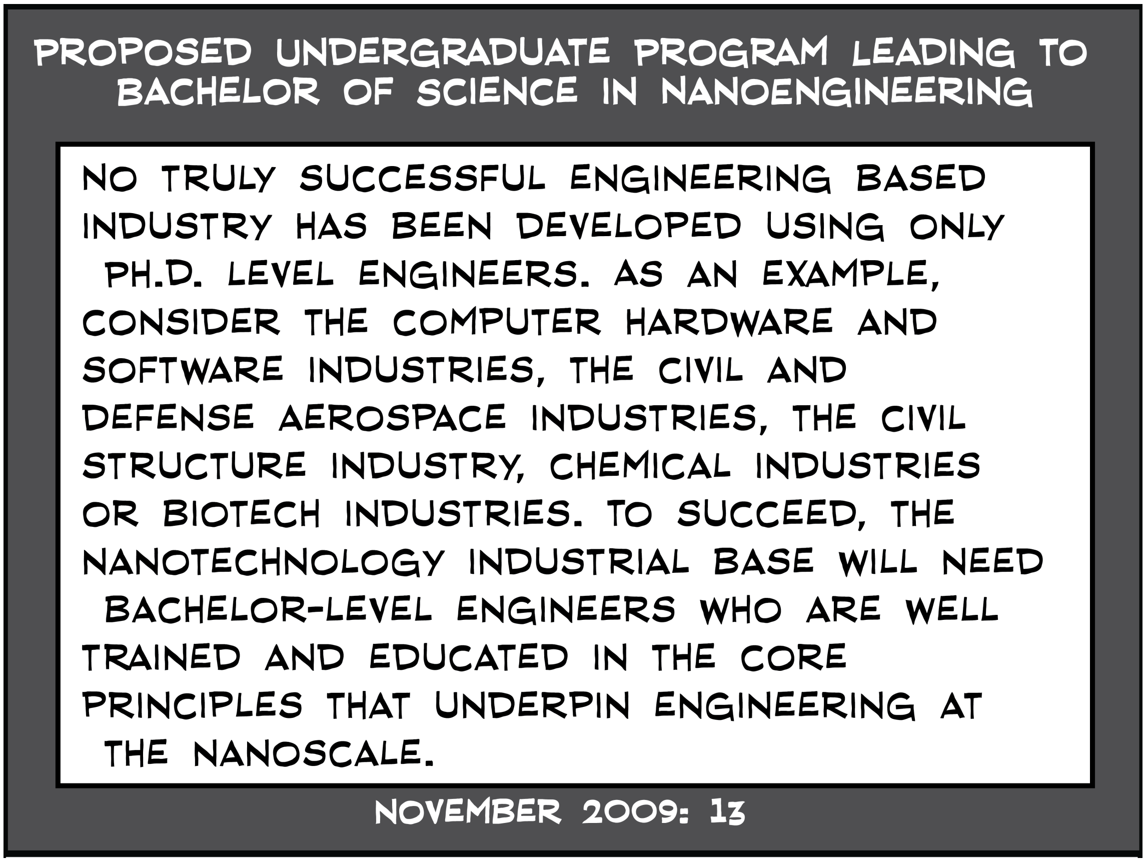

Illustration 114 Department proposal for undergraduate major. "No truly successful engineering based industry has been developed using only Ph.D. level engineers. As an example, consider the computer hardware and software industries, the civil and defense aerospace industries, the civil structure industry, chemical industries or biotech industries. To succeed, the nanotechnology industrial base will need bachelor-level engineers who are well trained and educated in the core principles that underpin engineering at the nanoscale."[76]

The department proposal frequently refers to these graduates as the "workforce" of the industry. That is, while some students may obtain patents even as undergraduates, and some will pursue graduate degrees and from there start companies or join companies in a leadership role, many will obtain jobs—highly paid, certainly, but jobs nevertheless—that do the lab work. Competition between students, unequal and unevenly distributed opportunities, and students' own interests work to place them in different tiers of this

76. Ibid., 13.

industrial base. As human capital, they can pursue their nano dreams, so long as they align their nano dreams with those of their industrial employers. While the specific term "human capital" is infrequently invoked, therefore, entrepreneurialism and innovation become the catchwords through which the central characteristics of human capital can safely promulgate: individuals who are always marketable and able to attract investors through their ongoing training, who see themselves as leaders and entrepreneurs even when they may be job-holders and workers, and who contribute to the common good by aligning their world-building projects with the market-based possibilities and constraints of capitalist technological innovation.

From Political Citizenship to Economic Citizenship

This multivocality of university, industry, and state regarding the purpose of the university is rendered more univocal insofar as the dominant imperative of each is capital enhancement. To the extent that the university produces human capital, it is engaged in enhancing its own capital as well. At first glance, it would seem that constituting graduates as human capital may be a relatively subtle shift for the figure of the engineer, who has historically embraced the imperatives of capitalism and at the turn of the 20th century was expected to work in managerial roles. According to Noble, any distinction between technology and capitalism is "collapsed in the person of the engineer and in his work, engineering."[77] But embracing capitalism and operating as human capital are not necessarily the same thing. The shift from political citizenship that embraces capitalism

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77. Noble, *America By Design*, 34.

to economic citizenship that *is* capital is one that significantly redefines what it means to be a citizen at all.

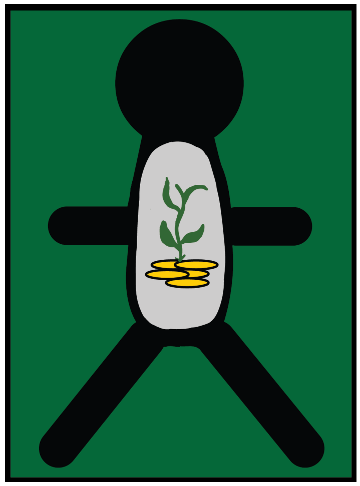

Illustration 115 Economic citizenship.

Notions of citizenship are being refigured when universities produce students as human capital. Often this argument is presented in terms of distinct, mutually exclusive categories. For example, Rebecca Lave argues that universities have been increasingly re-envisioned as providers of human capital, rather than educational institutions that prepare students for citizenship.[78] While I agree with the broader point she is making, what is at work here challenges a straightforward opposition between human capital and citizenship. Indeed, even as Brown argues that *homo oeconomicus* as human capital represents a significant rupture from its figuration in modernity—one that signals the end of humanism and that has disastrous consequences from democracy—she nevertheless

78. Rebecca Lave, Philip Mirowski, Samuel Randalls, "Sts and Neoliberal Science" *Social Studies of Science* 40, no. 5 (2010): 665.

marks it a "remaking" of citizenship.[79] I suggest that rather than producing human capital instead of citizens, the university (in conversation with state and industry) participates in redefining citizenship, including what counts as the proper knowledge of a good citizen. The citizen produced by this engineering school is not the citizen of the 1930s or 40s who was prepared to accept a large bureaucratic state or to be a political member of a polis. Rather, this is a citizen who is entrepreneurial and prepared to participate in the "commercialization of discoveries" as labor in the "local, national, and global entrepreneurial workplace."[80] The citizenship of human capital is economic, and the proper knowledge of this economic citizen includes the ability to look to the market to identify suitable problems and to translate technical solutions.

Yet even these characteristics of human capital are subject to change because ultimately human capital is a brand of citizenship that is defined by the market, meaning that it has no intrinsic content. Bill Readings argues that a key shift in the university post-1968 is that it replaces the principle of culture, instantiated by the German Idealists in service of the nation-state, with that of excellence, a techno-bureaucratic idea that has no referent.[81] No referent means that it has no content; what specifically counts as excellence at the level of the university or at the level of any unit within it is somewhat arbitrary and internal. I suggest that human capital is somewhat analogous; not that capital has no

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79. Brown, *Undoing the Demos*, 40. She also says, "The replacement of citizenship defined as concern with the public good by citizenship reduced to the citizen as *homo oeconomicus* also eliminates the very idea of a people, a demos asserting its collective political sovereignty" (39). Here there is still citizenship, only it has changed.

80. http/::www.calit2.net:newsroom:release.php%3Fid=1123, accessed June 29, 2015.

81. Readings, *The University in Ruins.*

content, but its content is determined by what is valued in the market in a given place and time. Sheila Slaughter and Gary Rhoades, articulating a similar idea in terms of "academic capitalism" write:

> When students graduate, colleges and universities present them to employers as output/product, a contribution to the new economy, and simultaneously define students as alumni and potential donors. Student identities are flexible, defined and redefined by institutional market behaviors.[82]

What constitutes students as human capital is not just their flexibility of identity, but their aptitude and willingness to continually reconfigure themselves to maximize their capital valuation by the marketplace. Indeed, doing so is part of being a good citizen.

The subject of human capital, in its ideals, is one that is thoroughly economic. Brown argues that human capital does not constitute political citizenship in part because "it vanquishes the subject that governs itself through moral autonomy and governs with others through popular sovereignty."[83] However, in suggesting that moral autonomy is compromised when a person, as human capital, is constrained to act and make decisions that will lead to capital accumulation, Brown's argument might seem to ignore the ways in which laborers within market-based economies have always been constrained by the market for their labor. As Luc Boltanski and Eve Chiapello note:

> The wage-earner is theoretically free to refuse to work on the terms offered by the capitalist, just as the latter is free not to offer work on the terms demanded by the worker. The upshot is that, while the relation is unequal in the sense that the worker cannot survive for long without working, it is nevertheless markedly different from forced labour or

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82. Sheila Slaughter and Gary Rhoades, *Academic Capitalism and the New Economy : Markets, State, and Higher Education*, Baltimore: Johns Hopkins University Press, 2004, 2.

83. Brown, *Undoing the Demos*, 79.

> slavery, and thus always involves a certain amount of voluntary subjection.[84]

Is the voluntary subjection of human capital who must align her income-stream with capital accumulation for herself and her firm and nation, fundamentally different from the voluntary subjection of the wage laborer who must sell her labor to the capitalist? Brown's argument also recalls to mind the belief that liberty—a belief associated with republicanism, but embraced by both republican and liberal understandings in the colonial era[85]—requires economic independence enabled by property. Is her concern with moral autonomy so different from Thomas Jefferson's sentiment that "dependence 'begets subservience and venality, suffocates the germ of virtue, and prepares fit tools for the designs of ambition,'" or Sir William Blackstone's argument that "men without property would inevitably fall 'under the immediate domination of others'"?[86] Key to her argument and what constitutes a rupture from the liberal capitalist worlds described by these statements is that while *homo politicus* and *homo oeconomicus* existed side-by-side throughout modernity, with neoliberal rationality *homo oeconomicus* comes to replace *homo politicus* rather than co-exist with it.[87] And it is on the terrain of discourses and

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84. Luc Boltanski and Eve Chiapello, *The New Spirit of Capitalism*, London; New York: Verso, 2005, 7.

85. Eric Foner, *The Story of American Freedom*,1st ed. New York: W.W. Norton, 1998, 8-9.

86. Ibid., 9.

87. Brown, *Undoing the Demos*; Foucault, *The Birth of Biopolitics.* Brown shows that while *homo politicus* was marginalized with modernity, it nevertheless existed alongside *homo oeconomicus* until this rupture enacted by the ascendance of a neoliberal rationality that renders the citizen only and always *homo oeconomicus*. Building on Aristotelian definitions of *homo politicus*, she variously defines this in relation to popular and individual sovereignty, "self-rule in a settled association that comprises yet exceeds basic needs," and human freedom (87). Foucault highlighted as early as the 1970s the dominance of *homo oeconomicus* and its shift under neoliberalism from a figure who was a partner of exchange to a figure who was an entrepreneur of himself (226). Brown builds on this while critiquing Foucault's lack of attention to

ideals that Brown grounds her analysis, arguing that while the ideals of liberalism and humanism—including freedom, equality, justice, and the public good—have not manifested in liberty or equality for all, they have nonetheless enabled struggles for greater emancipation. The promise of universal equality, the language of natural rights, and the horizon of the democratic imaginary have been fundamental to these struggles. It is with the loss of a subject who would strive for these ideals that neoliberal rationality particularly threatens democracy.[88] By rendering all domains subject to economic analysis, and shifting all political discourse to an economic register, "the knowledge and the cultural orientation relevant to even the most modest practices of democratic citizenship" are threatened.[89] To be clear, this is an argument about the potential ramifications of continuing along a particular trajectory of economization. I share this concern, and think it is relevant to my analysis of the institutional goal of producing human capital, but that is not to say that I see in this department and curriculum the end of political life. Rather, I think this is the pertinent framework within which to consider what specifically it means to teach science as economic conduct, and within which to understand the imaginaries of nano dreams and nano worlds that are at work here.

So while in light of Brown's analysis it might be questionable to continue calling the subject of human capital a "citizen," I regard the university's production of human capital as the ideal it strives for rather than a totally achieved state, and an ideal that

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the figure of *homo politicus*. She argues that only by understanding that with the ascendance of neoliberal rationality *homo politicus* is extinguished can one see the full impact of neoliberal rationality on democracy.

88. Brown, *Undoing the Demos*, 44, 111.

89. Ibid., 22.

potentially refigures citizenship rather than dismantling it entirely. The on-going production of human capital (and attempts to produce human capital which also might fall short) potentially maintains some of the discourses and ideals of democracy. I hold on to the language of citizenship for three reasons in particular: first, the university's role in mediating between state, industry, and citizen in producing this subject is continuous with its historical role in producing citizens in response to and for state and industry; second, this subject is constituted within a set of discourses that figure human capital as a good (and I mean that in both senses, as a product and as a socially and politically responsible entity who contributes to the common good); and finally, emphasizing the ways in which citizenship is being refigured rather than eliminated still highlights the political consequences of this shift while also enabling the identification of the ways in which this transmogrification of state and citizen is incomplete. This is important for identifying possible interventions, such as the pedagogical intervention I proposed in Chapter 3 regarding the lectures that introduce students to scale.

In considering the rhetoric I have observed in the NanoEngineering Department, while there is little explicit discussion of the political, or of concerns about liberty or justice,[90] there is frequent invocation of the public and common good. Entrepreneurialism, for example, is not usually presented in terms of personal economic gain. It is instead presented as how to best innovate for the benefit of society. The good of human capital—at least in my site—is constituted as adherance to the notion that one

90. Many individual faculty members are actively engaged in trying to support diversity efforts in nanoengineering, and in mentoring students from marginalized backgrounds. My point refers to collective discussions of such matters, or any incorporation of these subjects into the undergraduate curriculum.

of the best ways to serve one's fellow citizen on local, state, national, and global levels is through entrepreneurial innovation, which produces technological progress and economic activity. While this may be critiqued as offering only private notions of good or as understanding the good only in terms of economic conduct, or as constituting only a weak notion of a collective polity, I think it can also be seen in terms of a continuation of the classical liberal idea that the market is best positioned to reconcile individual and common good. I say this not as a defense of liberalism but to point out that there is still a discourse of individual and public good, and the hope that they can be aligned, even as I have critiqued (in Chapters 1, 2, and 3) the ways in which "benefit for society" is articulated in this site as a universalizing term that is always bound up with the promissory visioning that is necessary to attract capital. Still, the nano dream discourse reflects more than just capital accumulation.

In fact, the nano dream represents exactly this hope of uniting individual and collective good: it is the nanoengineer's dream of a future nanotechnology that will benefit society, that guides her research and career trajectory, and that is implicitly enabled and constrained by the market. The nano dream is the object of a liberal, not just a neoliberal, logic. The promised benefit of the nano dream includes but also exceeds the economic activity generated by its pursuit. And in pursuing it, the nanoengineer is figured as a subject of interest, not just as a subject of self-investing capital. The nano dream further works to justify the nanoengineer's committed participation in the industrial workforce that ostensibly will deliver on its promise to benefit society. Boltanski and Chiapello argue that capitalism has always required justification beyond a paycheck for a worker to demonstrate commitment to her job:

> The quality of the commitment one can expect depends upon the arguments that can be cited to bring out not only the advantages which participation in capitalist processes might afford on an individual basis, but also the collective benefits, defined in terms of the common good, which it contributes to producing for everyone. We call *the ideology that justifies engagement in capitalism* 'sprit of capitalism'.[91]

To the extent that the nanoengineer understands herself as pursuing a nanotechnology that will benefit society, she will be committed, at least in theory, to do the difficult labor for her industrial employer in a way that is committed (that is, she will do more than merely show up, but will work hard). However good her income may be relative to that provided by other forms of labor, it is not what shareholders in the company will receive if the technology successfully goes to market. The additional justification for her commitment is provided by the potential of fulfilling her nano dream of benefitting society. But if she is already and only human capital, why would the nano dream be necessary? Why would capitalism require any justifications? Wouldn't she merely consider her job in terms of investments and returns?

Universities have never been the only sites for producing political citizenship; to suggest they are would imply that those who do not have the means to attend university are precluded from practicing citizenship even if they are citizens. But if the university remains a central institution through which citizenship is produced, yet the citizenship it is producing is one that increasingly marginalizes *homo politicus* and increasingly comes to champion only *homo oeconomicus*, then this may indeed indicate a near future in which there are no longer democratic ideals or subjects who aspire to them.

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91. Boltanski and Chiapello, *The New Spirit*, 8, emphasis original. This coming together of individual and general benefits that support 'workforce participation' are what they refer to as the "justifications" of capitalism, drawing on Max Weber's emphasis on individual justifications and Albert Hirschman's emphasis on general justifications. See Boltanski and Chiapello, *The New Spirit*, 9.

Nanoengineering students are learning to becomes citizens whose adherence to the norms of good citizenship lies increasingly in their (techno)capital enhancement. In the arena of science and engineering, *homo oeconomicus* must align world-building with capital enhancement as students become human capital, and in this even the nano dream may be lost. Brown writes:

> Human capital is not driven by its interests, as was *homo oeconomicus* of yore. Nor is the classical liberal subject free to make its life and choose its values at will. Rather, human capital is constrained to self-invest in ways that contribute to its appreciation or at least prevent its depreciation; this includes titrating inputs such as education, predicting and adjusting to changing markets in vocations, housing, health, and retirement, and organizing its dating, mating, creative, and leisure practices in value-enhancing ways. Human capital is distinctly not concerned with acquiring the knowledge and experience needed for intelligent democratic citizenship.[92]

By "intelligent democratic citizenship," she is referring to two things: first, citizenship "as a practice of considering the public good," and second, citizens who are "modestly discerning about the ways of power, history, representation, and justice."[93] In the nanoengineering program, the first is maintained, but refigured. Nanoengineers become citizens who do indeed orient themselves toward the public good, but public good is understood in such a way as to collapse the distinction between public and private. The oft-repeated phrased "benefit of society" in this department and in science and engineering more broadly is imagined as a kind of public good produced through technological innovation. It is implicitly understood that this technological innovation occurs through private means. This is a so-called public good achieved through the

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92. Brown, *Undoing the Demos*, 177.

93. Ibid., 179.

marketplace, that is thoroughly privatized and only available to those members of the public who can obtain it there. If it is politics, it is not pursued through political action but through economic conduct. This is something I will explore in more detail in Chapter 6. Brown's second formulation of citizenship, where a citizen is able to critically engage questions of power, history, representation, and justice, is at times articulated as desirable (see, for example, language in *2020*), but is imagined as something that occurs through the general education requirements of a student's home college. Students do not learn to engage these questions in conjunction with science and engineering, by design. And yet the science and engineering classroom, as I have argued in chapters 2 and 3, is also a possible site of resistance, where the terms of economic citizenship might still be challenged.

Human Capital and Labor

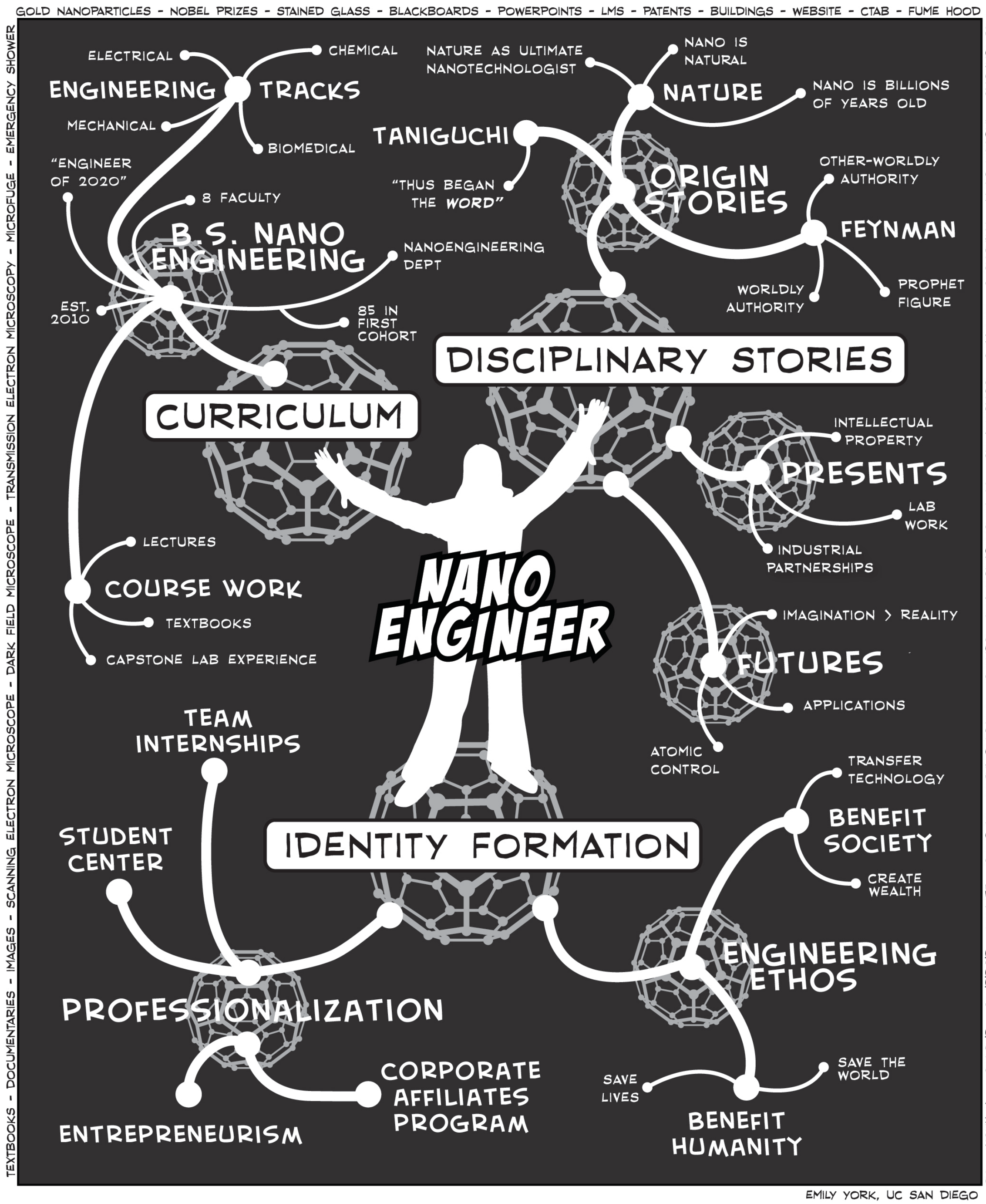

Illustration 116 Becoming a nanoengineer.

For students, becoming human capital means becoming self-investing entrepreneurial risk-takers able to succeed within the rules of competition and individual advancement, which is to say, they are to do labor without understanding themselves as laborers or having collective ties as labor. They are encouraged to see themselves instead as capitalists, even as they are expected to be the workforce, to occupy a position of being "monopolized and regulated as industrial resources."[94] It might seem self-evident that industry benefits from this, but why would the state? Perhaps because in the individualized, entrepreneurial worker, the state has a subject who is "committed," in the language of Boltanski and Chiapello that I previously referenced. She continually invests in her capital through education, training, and health maintenance. She has neither firm nor state to blame, and has little recourse when these investments fail to produce returns, either when she is laid off or experiences stagnant wages. She has no bonds with her fellow laborers upon which to forge bargaining or resistance, and the primary response to such a failure of investment is not resistance or resolution, but rather to invest more—retraining and retooling her skillset to match the changing marketplace for her labor.

She might also be considered a "reserve labor force"—having important technical skills, which is important for the state's military and industrial needs, but also the ability to learn new technical skills if and when her current skillset is no longer in demand. Chandra Mukerji shows how highly skilled scientists—in her case, oceanographers—continued to receive funding from the federal government even though their work had no

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94. Noble, *America By Design*, 44.

direct return to the government.[95] She argues that underlying this was the production of these scientists as a standing reserve of labor, there to be called upon in times of war when the government might need their scientific abilities. She purposefully uses the term "reserve labor force"—but argues that in this case, the term has more in common with the Reserve components of the Armed Forces than the economic term for underskilled labor who can be employed during boom times and laid off again during downturns.[96] Yet, with nanoengineers as human capital both connotations of the term are relevant. The military, national labs, and defense contractors are potential employers of graduates of this program, and act as significant funders for academic and industrial labs. Engineers thus employed may be called upon to contribute their skills and know-how in times of war. Yet graduates are also potentially expendable as industrial resources. If they don't continually self-invest in their capital (and even if they do), they may not survive downturns in the economy. *2020* says that for an engineer to be "individually/personally successful" they will have to "learn continuously throughout his or her career."[97] It suggests that this is because technology will continue to change quickly and because the "career trajectories of engineers will take on many more directions," including engaging with different parts of the world, different types of people, and different objectives. This is undoubtedly a reasonable forecast, but the imperative to continuously learn must also be read through an anxiety articulated earlier in the report: that under the terms of

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95. Chandra Mukerji, *A Fragile Power : Scientists and the State*, Princeton, N.J.: Princeton University Press, 1989.

96. Ibid., 7.

97. *2020*, 56-7.

globalization, engineers may expect their jobs to be outsourced and/or have to compete with immigrant engineers. In order to compete in this world, one must continually self-invest, in part through training.

While nanoengineers are encouraged to identify their nanotechnology dreams, and to imagine their career trajectory in terms of their technological desires, the individualism implicit in such dreaming is in tension with the imperatives of labor and team work. The department repeatedly emphasizes that its students need to learn how to work on a team, and this is built into the curriculum, particularly in the two-quarter capstone laboratory course in which students are placed on teams to conduct small research assignments. Yet, the team, as Noble notes, is ultimately the "corporate team"[98] that engineers will be hired into, where they will labor toward the team's goals as directed by the company. Even if engineers stay within academia where they may exercise more direction over their research pursuits, they will be tethered to the demands of funding, and the on-going efforts of procuring it, which supports their lab and both enables and constrains the dreams they may pursue. While the team may provide for sociality, it does not stand in for the collective ties of labor. The lack of a collective identity connoted by human capital challenges any class consciousness or union ties. As I've previously noted, however, while their status as human capital may make it even more difficult to develop a collective identity, this is not necessarily something new for engineering as a profession. As Noble points out, there is a longstanding tradition of individualism and anti-unionism within the engineering profession, as the professional engineer from the turn of the

98. Noble, *America By Design*, 49.

century on was often also in management, or was at least expected to be part of the corporate machinery. In this sense, the emergence of human capital theory and its imbrication in neoliberal rationality is perhaps less a dramatic turn of events for engineering than for other disciplines and professions.[99]

This individualism may be continuous with engineering historically and many nanoengineers may be content with what they're doing, as human capital or otherwise. If, as the department proposal suggests, the average salary for an engineer working in nanotechnology with just a bachelors degree in the U.S. is approximately $91K, then perhaps this is a promising career trajectory for these engineering students.[100] Yet, as is acknowledged in *2020,* job prospects today are not necessarily indicative of what they will be. Nano dreaming that works to justify workforce participation would be undermined if it acknowledged the precarity of human capital or the market constraints at work in the dream and its pursuit.

Producing Investable Futures

> Democracies are conceived as requiring technically skilled human capital, not educated participants in public life and common rule.
>
> —Wendy Brown[101]

If the nanoengineer is human capital whose entrepreneurialism is directed at ways of exploiting the nanoscale for capital enhancement, what does this mean for science?

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99. That said, it is not clear yet what kind of working conditions students will face as part of the workforce of the nanotechnology industry, given that it is a new industry and that there is not a single concentrated nanotechnology workforce that I can identify.

100. Esener et al., *Proposal for the Creation*, 20. The Proposal cites a survey conducted by *Small Times* magazine for this data.

101. Brown, *Undoing the Demos*, 177.

Whether through public engagement or through technocratic governance, scientists and engineers are frequently sought to participate as experts in science policy. While they may indeed have expertise on science or technology and I am not suggesting that they should not therefore play a role in science policy, it is nevertheless important to understand that their production as experts, as I have argued in this chapter, may be coterminous with their production as human capital.[102] While scientists have never been disinterested figures, their centrality to matters of science policy in a neoliberal state does not even presuppose or require their disinterestedness. Within the dynamics of neoliberal rationality, in which the state's primary role is to create and maintain markets (and as part of that, creating and maintaining the infrastructures of innovation)—the entrepreneurial scientist or engineer as human capital is perhaps the ideal figure—from the perspectives of the state, the university, and industry—to perform technocratic governance that is organized around capital enhancement and the materialization of investable futures.

In tracing historical conceptions of the scientist, Steven Shapin shows that there is a close connection between changing ideas about the character of the scientist and understandings of what scientific knowledge is, how it is produced, and how it is imbricated in structures of power and wealth.[103] As I've briefly outlined, others have shown that science and engineering in particular have a long history of engagement with market logics, as does the research university. The distinction between basic and applied

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102. This is not to say that non-STEM students are not also being produced as human capital, which is what leads Brown to her concern about the ways in which producing subjects exclusively as *homo oeconomicus* undermines the conditions for democracy.

103. Shapin, *The Scientific Life,* 14-15.

science was never clear cut in practice. And the drive toward intellectual property, technology licensing, and spin-offs became widespread in the 1980s in the era of biotechnology and the Bayh-Dole Act of 1980 that allowed universities to own the intellectual property rights from research that was federally funded. The scientist/engineer as human capital does not necessarily signal a simple shift, then, toward a mode of knowledge production that is *more* commercial, privatized, or dependent on industry. But the production of intellectual and human capital does signal the economic measure of the engineering school's outputs. In this context, it is important to note that this is a mode of engineering that denies any distinction between science and engineering, or between basic and applied research. Daniel Bell noted a changing relationship between science and technology in the early 1970s, when he argued that there was a rise in science-based industries and that inventions and innovations were increasingly dependent on new scientific research.[104] At the same time, his arguments about the "post-industrial society" as a "knowledge society" take for granted distinctions between basic and applied research, and between science and engineering.[105] In the 21st century Jacobs School of Engineering, the very categories of science and engineering that have historically distinguished different modes of activity are being destabilized. Science and engineering are deeply intertwined, and engineering does not merely dress up as science for prestige as it might have in the early 20th century. Engineering is refigured as indistinguishable from science—particularly in a nascent field like nanoengineering,

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104. Daniel Bell, *The Coming of Post-Industrial Society : A Venture in Social Forecasting*, Special anniversary ed., New York: Basic Books, 1999, 196-8.

105. Ibid., 212-32.

where fundamental research about the properties and behaviors of the nanoscale is required in order to innovate new technologies. Indeed, the dean of the school, at the time I interviewed him, explicitly claimed that there was no difference between the two.[106] As I will show in the next chapter, the term "translational research" places all modes of research within a temporal trajectory that ultimately culminates in knowledge's translation in the market to product. Therefore, to say that the nanoengineer as human capital is necessarily measured according to the economic value of what she produces should not be discounted based on the idea that this has always been true of engineering. Any distinction between science and engineering, or between basic and applied research, or between knowledge production and technological innovation, is irrelevant to the project of capital accumulation. Rather, knowledge production *is* innovation, and the knowledge worker—insofar as she delivers a return on the investment that was made into her capital—*is* an innovator. Indeed, human capital theory posits that innovation, and therefore economic growth, depends on capital investment in this knowledge worker:

> If there is innovation, that is to say, if we find new things, discover new forms of productivity, and make technological innovations, this is nothing other than the income of a certain capital, of human capital, that is to say, of the set of investments we have made at the level of man himself.[107]

The nanoengineer as human capital is not a worker who sells her labor power, but as Foucault shows, is a "machine/[income]stream complex," or "a conception of capital-ability which, according to diverse variables, received a certain income that is a wage, an

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106. Interview with the dean, September 9, 2011.

107. Foucault, *The Birth of Biopolitics*, 231-32.

income-wage, so that the worker himself appears as a sort of enterprise for himself."[108] That is, the nanoengineer is an entrepreneur after all, one who may not start a nanotechnology company but whose actions should deliver a return on her self-investment. Her investment in an undergraduate degree from UC-San Diego should result in an increased income stream, and her continued investment in education and training as a life-long learner should ideally maintain or increase that income stream. Her work as a scientist-engineer-innovator is done as an "enterprise-unit"[109] rationally assembling into the larger structures of the innovation regime within which she works. This enterprise unit must continually attract investors investing in her human capital and in the intellectual capital she attempts to produce, and these investors may come from the twin pillars of the state—both nonmilitary and military funders—or from industry.

The production of scientist-engineers as human capital, then, is at the same time the constitution of knowledge production as an economic form of world-building that necessarily pursues "investable futures."[110] The futures that can be dreamed and realized are ones that are "investable," or ones that have the greatest chance of providing a return to investors.

108. Ibid., 225.

109. Ibid., 225.

110. Shapin, *A Scientific Life*, 17. Shapin is specifically referring to how venture capitalists make decisions about what start-ups to invest in, but I am suggesting that the term applies more broadly to the project of technological innovation.

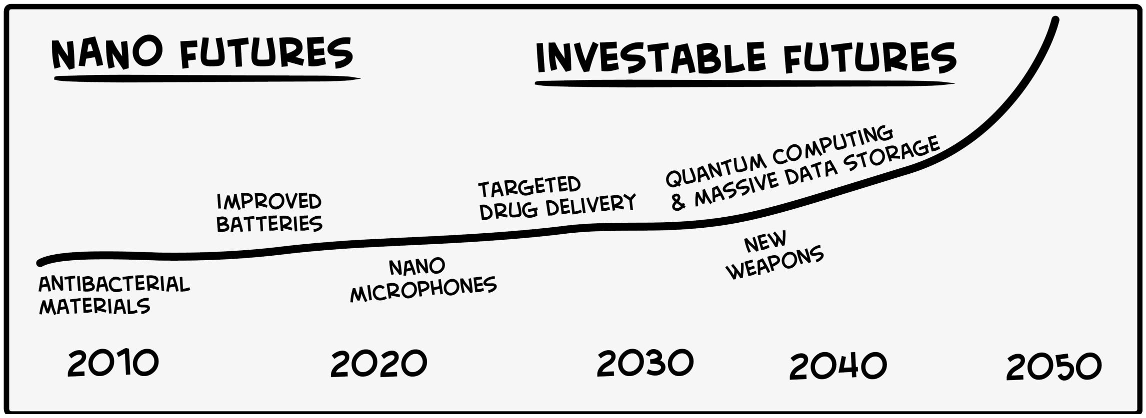

Illustration 117 Investable futures.

If it was true in the early 1970s when Bell was theorizing the post-industrial society that "most of the activities of science are outside the business system and the organization of science policy is not, in the first instance, responsive to business demand," this cannot be assumed today.[111] This raises an issue that is less a matter of conflict of interest for scientists as what Ruja Benjamin suggests is "a *lack* of constructive conflict over the priorities and governance of science."[112] That is to say that most knowledge production that has economic incentive—which may be most knowledge production—may not raise conflicts of interest per se. But to the extent that the determinants of value for this knowledge production are tied to the rational calculations of enterprise-units, or capitals, what counts as good science is investable science. The primary determinants of whether one project should be done and not another is the market, not the objectives of a political body.

111. Bell, *The Coming of Post-Industrial*, 232.

112. Ruha Benjamin, *People's Science Bodies and Rights on the Stem Cell Frontier*, Stanford, California: Stanford University Press, 2013, 5.

This primacy of the market in determining good science sidesteps discussions of democracy and science, which are often framed in terms of public engagement or as publically-informed science and technology policy that appropriately balances the benefits of innovation with the protections of public health, public values, and the environment. The scientist is a key figure in both public engagement and policy discourses, yet is often figured as a disinterested subject adhering to Mertonian norms (communalism, universalism, disinterestedness, and organized skepticism[113]) who represents neither state nor industry as such but rather the objective truth of science. Therefore the production of scientists and engineers as human capital should be understood not only in terms of the shift from political to economic citizenship, but also in terms of the role the scientist plays specifically in addressing questions of science and technology in a democracy.

The argument for public engagement generally appeals to the instrumental value in lay and local knowledges, and to the rights of citizens in a democracy to weigh in on technoscientific issues, either because public funding supports early research or because the downstream effects of such research have social, environmental, and ethical implications for citizens. Bryan Wynne, for example, has argued for "upstream" public engagement concerning nanotechnologies, not only to better anticipate risks, but to

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113. Robert Merton, "The Normative Structure of Science," In *The Sociology of Science : Theoretical and Empirical Investigations*, edited by N. W. Storer, 267-78, Chicago: University of Chicago Press, 1973; See also John Ziman, *Real Science What It Is, and What It Means*, Cambridge ; New York: Cambridge University Press, 2000.

deliberate on the shaping of future worlds.[114] Philip Kitscher argues that allowing publics to participate in setting research agendas would do better than existing institutions or market forces to ensure that such agendas are in line with social justice.[115] And Colin Farrelly explicitly relates the principle of inclusion to responsibility, arguing that publics should have the opportunity to participate in deliberation concerning the regulation of nanotechnology, that those with specialized knowledge have a moral responsibility to inform the public about the likely benefits and costs of nanotechnologies, and that “responsible law” requires the inclusion of various deliberative bodies in negotiating competing values and stakeholder claims.[116] “Responsible Innovation” is a key term particularly in European discourse, where the language of responsible innovation has been incorporated into EU governance, and generally attends to these competing values and stakeholder claims.[117]

Yet the promise of public engagement to democratize science assumes dialogue, in which scientists as experts and citizens as non-experts participate. It is implicitly, if not explicitly assumed that the representatives of science are distinct from representatives of

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114. Phil Macnaghten, Matthew B. Kearnes, and Brian Wynne, "Nanotechnology, Governance, and Public Deliberation: What Role for the Social Sciences?" *Science Communication* 27, no. 2 (December 1, 2005): 282.

115. Philip Kitscher, "Scientific Research - Who Should Govern?" *NanoEthics* 1 (2007): 177-84.

116. Colin Farrelly, "Deliberative Democracy and Nanotechnology," In *Nanoethics : The Ethical and Social Implications of Nanotechnology*, edited by Fritz Allhoff, xxiv, 385 p. Hoboken, N.J.: Wiley-Interscience, 2007, 222.

117. See, for example, work in the Journal for Responsible Innovation and work in the edited volume Responsible Innovation (Richard Owen, J. R. Bessant, and Maggy Heintz, *Responsible Innovation Managing the Responsible Emergence of Science and Innovation in Society*, Chichester, West Sussex: John Wiley & Sons Inc., 2013).

industry. Proponents hope that these exercises will produce more responsible innovation—socially responsible, because it would be more aligned with the needs and values of wider publics, would consider issues of distributive justice, and would be in line with democratically determined values; technically responsible, in that risks may be identified sooner and thus prevented; and economically responsible, in that future public controversies might be avoided, thus ensuring greater public uptake of technologies. Others have critiqued public engagement on the grounds that it is merely part of the project of technology commercialization. Charles Thorpe and Jane Gregory, for example, argue that participation disciplines subjectivities and publics as markets.[118] Rather than allowing deliberation on future worlds, as Wynne proposes, Thorpe and Gregory look at various initiatives in the UK, such as the GM Debate? exercise as closing down such visioning, operating instead to increase public confidence in technoscience and government regulation, and to discipline public participants as receptive consumers for technologies.[119]

In relation to these discussions regarding science and democracy, consider *2020*'s call for engineers to become leaders in policy and government, a call that is echoed in

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118. Charles Thorpe and Jane Gregory, "Producing the Post-Fordist Public: The Political Economy of Public Engagement with Science," *Science as Culture* 19, no. 3 (2010): 273.

119. In support of this argument, it is worth noting that in the United States, the NNI, which is the central federal hub of all nanotechnology endeavors, considers ELSI communities (those related to the ethical, legal, and societal issues surrounding nanotechnology) as consisting of consumers, engineers, ethicists, manufacturers, nongovernmental organizations, regulators, and scientists. Industry representatives are not listed as such, though scientists or engineers could be employed by industry. But importantly also note that they do not list citizens as such. While public engagement is an explicit aim of the NNI, nowhere is the word "citizen" mentioned. Incidentally, a search on the NNI website for the word "citizen" turned up zero results, while a search on the word "consumer" turned up two pages of results. http://www.nano.gov/you/ethical-legal-issues, accessed 05/22/2011.

national and state fellowship programs that provide policy experience for postdoctoral scientists and engineers (see, for example, the California Council on Science and Technology's Science & Technology Policy Fellow program, which is "a unique professional development opportunity to scientists and engineers" and is "ideal for qualified applicants interested in improving the interface between science and legislative decision-making."[120]). And consider this too in relation to my discussion of the undergraduate curriculum in Chapters 2 and 3, in which I showed how nanoengineering is presented as intrinsically ethical. Through an analysis of the undergraduate curriculum, I showed that there is little critical engagement with the potential risks or downsides of nanotechnologies. I argued that there was little faculty modeling of reflexive thinking about science as part of doing science. While nanoengineering students are taught to orient their work toward the public good, even if they understand this in terms of private capital enhancement, it is less clear that they are being taught ways to critically engage questions of power or justice, and certainly not as questions that are relevant to their own work as nanoengineers. What skillsets would they bring to the policy table? *2020* recommends that engineering students be educated "to understand and appreciate history, philosophy, culture, and the arts" and claims that "the balanced inclusion of these important aspects in an engineering education leads to men and women who can bridge the 'two cultures' cited by the author C. P. Snow."[121] Yet within the research university any such exposure occurs separately from their training in science and engineering, again separating a students' engagement with science and engineering from what they may

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120. http://fellows.ccst.us/apply.php, Accessed January 7, 2015.

121. *2020*, 52.

learn of power, justice, history, and ethics in their general education courses.[122] It reinforces the notion that there is a fundamental separation between these two forms of knowledge and practice, and does not train students to think about power, justice, history, and ethics within practices of knowledge production and technological innovation.[123] Bill Readings, in his discussion of the emergence of excellence as the key principle of the contemporary university, frames this problem in terms of thinking:

> Thinking, if it is to remain open to the possibility of Thought, to take itself as a question, must not seek to be economic. It belongs rather to an economy of waste than to a restricted economy of calculation. Thought is non-productive labor, and hence does not show up as such on balance sheets except as waste.[124]

But human capital, as a rational enterprise-unit, must think outside its own terms if it is to engage in such "non-productive labor" as thinking, in Readings' sense. Scientists and engineers are potentially being asked to stand in as political actors in the domain of science and technology governance even as they are trained to approach knowledge production as economic conduct. Moreover, this is economic conduct that is structurally and logically independent from a critical or reflexive mode of thinking about science in relation to its social, political, and environmental dimensions. They are being asked to

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122. One notable exception in my interviews struck me: A student responded to my question about how ethics has come up for her by recounting a robust discussion she had had in a class about genetic research on Jewish people during the Holocaust. I asked her what class this was, and it turned out to be a history of science class taught in UC San Diego's Science Studies Program (Interview with NanoEngineering Student, May 23, 2012).

123. See Chapters 2 and 3, as well as Karen Barad's "Agential Literacy" article for a discussion of the importance of integrating these (Karen Barad, "Reconceiving Scientific Literacy as Agential Literacy: Or, Learning How to Intra-Act Responsibly within the World," In *Doing Science + Culture*, edited by Roddey Reid and Sharon Traweek, viii, 339 p. New York: Routledge, 2000).

124. Readings, *The University in Ruins*, 175.

stand in as political actors even as they are being educated to understand themselves primarily and perhaps even exclusively as economic actors. Therefore the primary discourse challenging the logic of investable futures—public engagement—is itself undermined by its reliance on the figure of the technical expert without acknowledging the ways that the technical expert's constitution as human capital is at odds with the goals of democratic science.

Conclusion

I have suggested that the production of nanoengineers as human capital does not represent a fundamental rupture in either science or the university, but also that it is indicative of how neoliberal rationality informs each. Importantly, it should be understood in the context of my previous arguments in Chapters 2, 3, and 4. The institutional goal of the engineering school to produce intellectual and human capital is inseparable from the ways in which a new department and undergraduate major have been established within it that articulates nanoengineering as innovation for the benefit of society. The nano dreams that are supposed to guide the career trajectories of the nanoengineer are not just about the nanoengineer's private motivations; the nanoengineer must learn how to articulate nano dreams that attract the capital investment necessary to innovation.[125] What nanoengineering faculty model for the students is how to articulate the promise of societal benefit, how to respond to concerns about risk in ways that allay investor fears, and how to demonstrate to potential investors (be they employers or

125. See Kaushik Sunder Rajan's discussion of promissory visioning and its role in securing investment for technoscientific innovation. Kaushik Sunder Rajan, *Biocapital : The Constitution of Postgenomic Life*, Durham: Duke University Press, 2006.

funders) that the nanoengineer as much as any specific nanotechnology research project is a good investment.

The university need not articulate the dual missions of research and education, or make special claims about its role producing citizens, when all of its activities can be brought under the imperative and logic of capital enhancement. The key indicator of whether it is successful at producing human capital is the income earned by its graduates, not whether those graduates vote, engage in critical thinking, or appreciate literature. Insofar as any of these latter attributes are important to potential employers and help secure an income, they may matter to capital enhancement, but this is difficult to measure. Therefore when the university website cites a source indicating that it has been ranked the sixth best value on the West Coast in terms of its alumni earning potential, it is claiming to be a good investment in one's human capital.[126] The production of intellectual and human capital signals not so much corporatization—which is not new—as much as the neoliberal rationality which subjects all domains to economic analysis, and figures all entities as capitals that can be processed by the market.

In the National Academy of Sciences report "Educating the Engineer of 2020" the committee quotes MIT President Charles Vest in 2004 addressing the "assembled educators and stakeholders" for engineering education:

> As we think about the plethora of challenges, it is important, in my view, to remember that students are driven by passion, curiosity, engagement, and dreams. . . . Despite our best efforts to plan their education, to a large

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126. "PayScale, a website that collects salary data, also listed UC San Diego as the 6th best college on the West Coast for the earning potential of alumni." http://ucsdnews.ucsd.edu/pressrelease/payscale_ranks_uc_san_diego_10th_best_public_university_for_alumni_salary_e , accessed January 7, 2015.

> extent we simply help to wind them up, and then step back to watch the amazing results.[127]

While steeped in the technoscientific imaginary of passionate and curiosity-driven world-building, Vest uses a mechanical metaphor to describe engineering students. Just wind them up. This metaphor evokes the imagery of mechanical dolls—able to move, but only in prescribed ways. Or, given my discussion of self-assembly in Chapter 4, it evokes the suspect autonomy of nanoparticles assembling without human intervention yet entirely according to the conditions produced by the engineer. Though said in a positive light, Vest's statement also recalls Mario Savio's counter: "We are human beings!" The convergence of science and engineering with neoliberal rationality reduces world-building to a kind of mechanistic calculus determined by the market and achieved through the labors of human capital. In such a world, where do passion, curiosity, engagement, and dreams fit?

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127. National Academy of Engineering, *Educating the Engineer of 2020: Adapting Engineering Education to the New Century*, Washington, DC: National Academies Press, 2005, xi-xiii. This report followed the original *2020* report that I have previously cited.

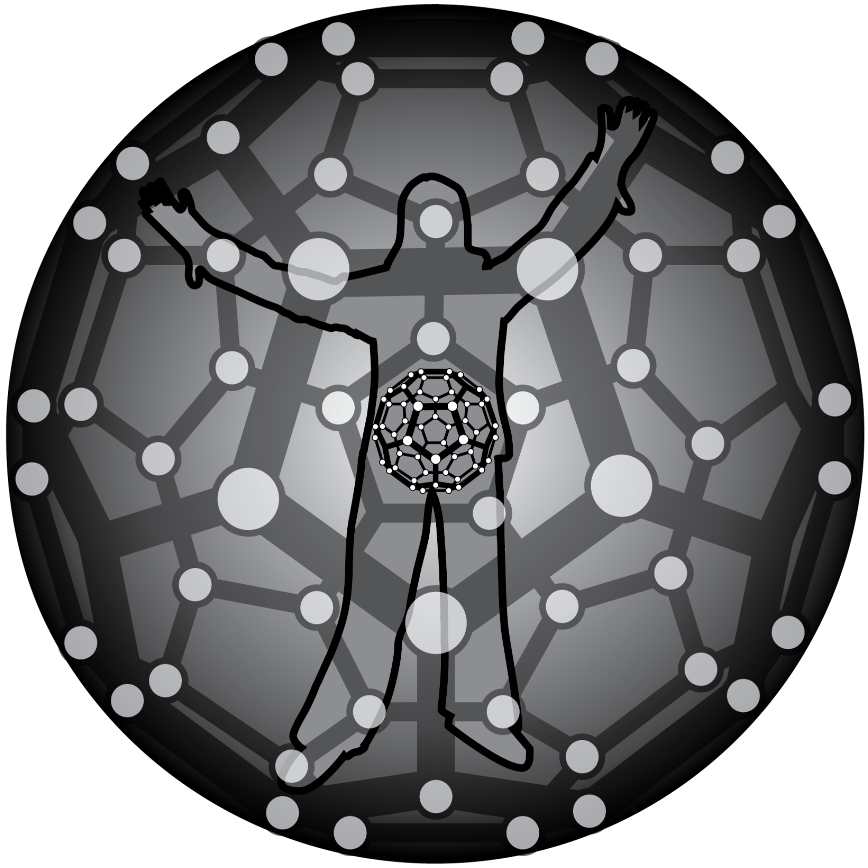

Illustration 118 Human beings, nanomachines.

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Chapter 6 Translational Research in an Innovation Ecosystem

> We are a small department, relatively speaking. We currently have 17 faculty. Those faculty manage in their research about $35 million … so it's a very successful department in terms of its research. We account for about ¾ of all technology disclosures from the [Engineering School], so again, very… innovative research activity. We also have started up quite a few companies. Our faculty are responsible for the creation of about fifteen companies over the course of their academic lives, so a lot of their work is, that we do in our research, we are very eager to translate into technologies for our society.
>
> —Chair, NanoEngineering Department[1]

Introduction

In Chapter 5, I focused on one half of the Jacob School's Vision Statement, the production of human capital. But both the Vision Statement and the dean describe another goal that is key to the school's vision: the production of intellectual capital. I suggested in Chapter 5 that the emphasis on producing human and intellectual capital was indicative of the ways that neoliberal rationality informs the school's raison d'etre, articulating knowledge production and education in terms of capital enhancement and economic conduct. Recall that the dean emphasized in his welcome speech to newly accepted undergraduates that there was a distinction between intellectual property and intellectual capital. While both categories would seem to imply some interest in income or profit, capital speaks directly to the imperative of continual capital enhancement and to the ways in which such capital enhancement is secured through circulation, or movement.

In Chapter 4, I also briefly examined the metaphor of self-assembly, arguing that the emphasis on individual autonomy and the lack of a "hand," or human intervention, in

1. Chair of the Nanoengineering Department, Intro I, April 9, 2011, transcribed by author.

producing functional structures echoes similar rhetorics in liberal and neoliberal theories. In this chapter, I want to take another look at how nanoengineers understand their research, though I will not be looking at laboratory practice but instead at faculty descriptions of their research in interviews, publications, and funding applications. In attempting to understand how their research and the discourses invoked in framing this research might align with the institutional vision of producing intellectual capital, I also want to return to the question I articulated in the Introduction (Chapter 1) regarding how nanoengineering comes to understand itself as innovation for the benefit of society.

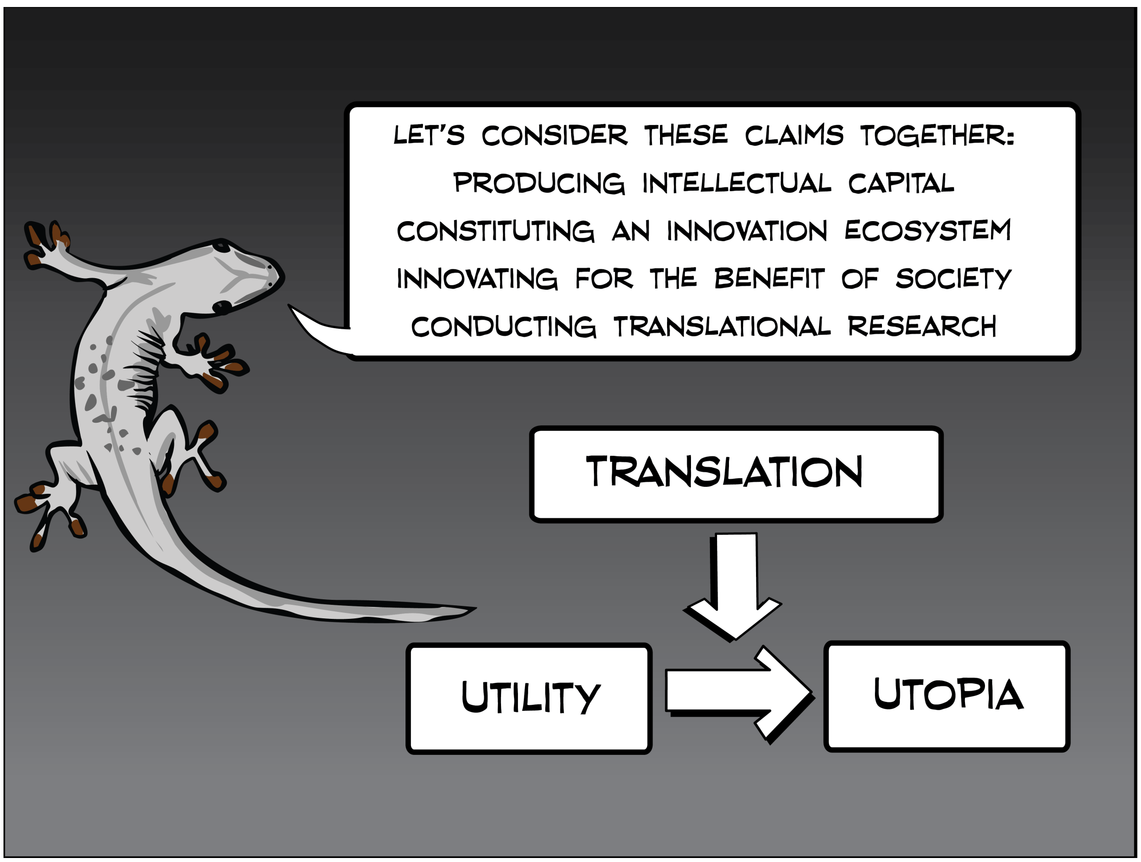

Illustration 119 Translation unites utopia and utility.

In faculty descriptions of research, the metaphor of translation aligns the two goals of producing intellectual capital and innovating for the benefit of society. If science and engineering within neoliberal rationality becomes the production of investable futures, as I claimed in Chapter 5, then translation becomes the governing idiom through which research is constituted as economic conduct that benefits society through both economic activity and technological progress. The goal of producing human capital materializes in the undergraduate curriculum in the form of entrepreneurialism; the goal of producing intellectual capital materializes in the department under the guise of translational research. The nano dream serves as promissory vision, motivation and inspiration, and justification for committed workforce participation and capital investment; it is the utopian horizon of nanoengineering. Translation speaks to the organizational, temporal, and teleological framework for research that, at any phase, is necessarily oriented toward the market. It speaks to the necessity of utility in producing innovation of products and processes that will be used by people, and articulates utopia in utilitarian terms.

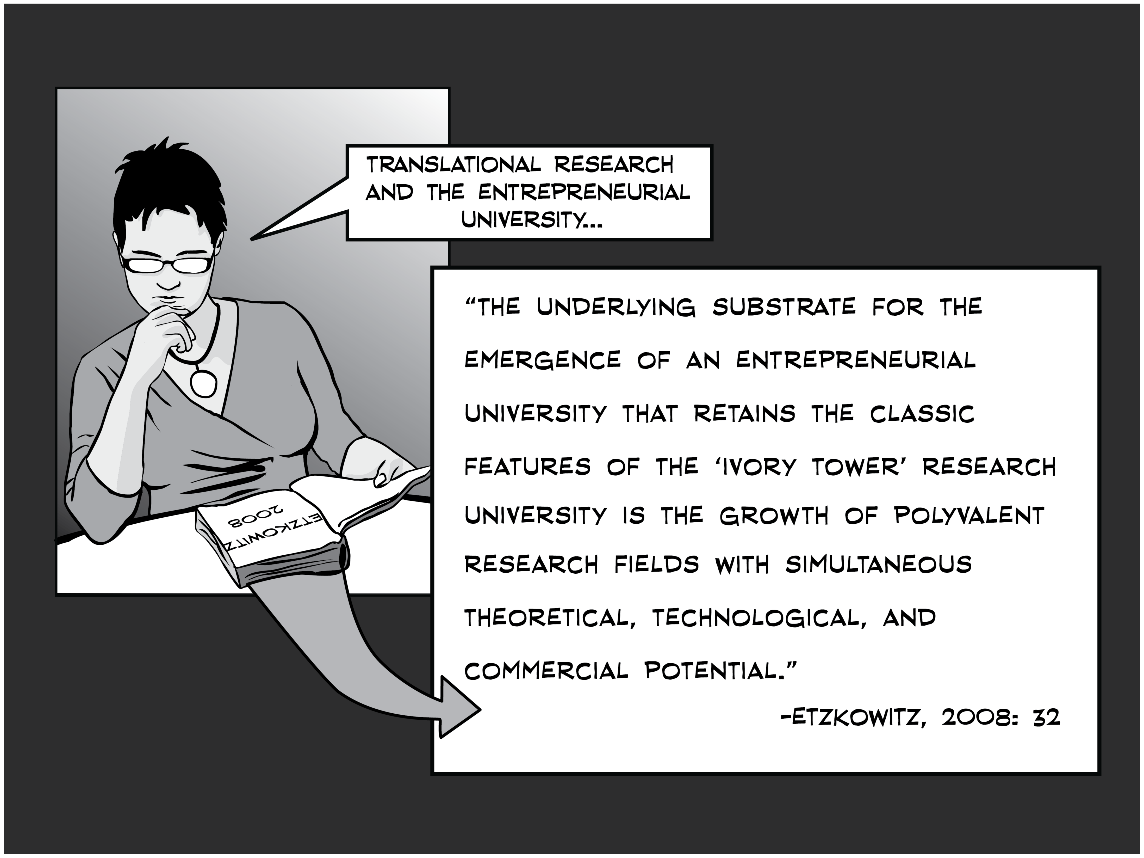

Illustration 120 Translational research and the entrepreneurial university. "The underlying substrate for the emergence of an entrepreneurial university that retains the classic features of the 'ivory tower' research university is the growth of polyvalent research fields with simultaneous theoretical, technological, and commercial potential."[2]

In this chapter, therefore, I want to understand how nanoengineering comes to be understood as translational research, how translation constitutes nanoengineering as economic conduct, and how it articulates the relationships between producing knowledge, enhancing capital, and benefitting society. I argue that the paradigm of translational research is taken up as the right tool for the job of aligning nanoengineering's goals of innovating for the benefit of society and producing useful things with the institutional

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2. Henry Etzkowitz, *The Triple Helix : University-Industry-Government Innovation in Action*, New York: Routledge, 2008, 32.

goal of producing intellectual capital. In Chapter 5, I argued that while distinctions between basic and applied research, and between science and engineering, were never clear cut, in this engineering school the dean has claimed that there is no distinction to be made between these categories.[3] In this chapter, I argue that translation replaces what are considered to be the defunct categories of basic and applied to connote research that effectively moves from the laboratory to society via the market. Translation places all phases of research—from research that attempts to produce knowledge about how something in nature works, to research that uses what is already known about nature to create new applications—into a linear continuum moving toward the market. In doing so, it implicitly figures all research as economic conduct. While research that is further conceptually and temporally from the market (from becoming a product that can be valuated by the market) may still be allowed and even encouraged depending on the context of such research, it must still be possible to articulate at least in broad strokes the translational trajectory of such research toward the market. That is, a researcher applying for funding must be able to articulate how, when, and in what form, their research might eventually reach society through the market. Translation signals the streamlining of innovation to produce useful objects of economic value with optimal efficiency. It also signals a shift toward governance insofar as the broader translational apparatus identifies and propagates best practices for successful translation.[4] By translational apparatus, I am

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3. I am not referencing the current dean, but the dean at the time of my interview.

4. For analysis of how governance works as a kind of anti-politics see Wendy Brown, *Undoing the Demos : Neoliberalism's Stealth Revolution*, First Edition, ed. New York, Cambridge, Massachusetts: Zone Books, MIT Press, 2015.

referring to the contingent set of institutions, funding structures, actors, and ideologies, that are at work in doing, framing, and understanding science and engineering in terms of translational research.

But just as I suggested in Chapter 5 that the production of human capital, or *homo oeconomicus*, does not necessarily mean in practice that the shift to neoliberal rationality is total and complete, the production of intellectual capital may eclipse but does not necessarily replace other values and goals of knowledge production in the NanoEngineering Department. Indeed, the Engineering School's vision statement notwithstanding, I have never heard faculty members in the department talk about their research explicitly in terms of intellectual capital, though they speak of funding and grants, technology disclosures, patents, corporate partners, and spin-offs. And in fact, even as translation orients all research toward the market and articulates this research as economic conduct, it simultaneously allows for a broad spectrum of research projects relative to their conceptual and temporal distance to the market. Many of the NanoEngineering faculty conduct a range of projects at the same time, some in partnership with industry that have a quick expectation of marketization and others in partnership with the state that are more theoretical and have a longer timeline before marketization is expected. Therefore, doing nanoengineering within the framework of translational research is both enabling and constraining—even as translation demands an efficient march toward the market, it affords the possibility of conducting research that cuts across the basic and applied categories it replaces. On the one hand, this may threaten the erasure of basic research, forcing all research to specify its potential marketization. On the other hand, it allows the nanoengineer some freedom that she may not otherwise have to pursue basic research, insofar as it exists within the translational continuum and is not labeled “basic.” Faculty members are able to navigate the demands of this translational continuum, skillfully leveraging their success at producing intellectual capital to, in effect, pursue their nano dreams. At the same time, neither basic research nor the nano dream exist apart from their enrollment in the commercialization that is paramount to the production of innovation and intellectual capital. In practice, these are not mutually exclusive states. Translation unites the utopian possibilities of technological progress and societal benefit with the utilitarian demands of efficiently commodifying knowledge production. While the market is the nexus of the translational apparatus that secures commodification, nanoengineers have some flexibility in how they articulate their research and themselves toward the market, so long as they do so.

Even as I turn my attention to nanoengineering research, my gaze is never far from the figure of the nanoengineer, and to the ways in which the production of a new discipline is necessarily a coproduction of the field and its consummate practitioners and imaginaries. In understanding the ways in which nanoengineering comes to be framed and articulated as translational research, I have come to see the nanoengineer also as a kind of translator. Through the translational, coordinating, and interpretive practices of the nanoengineer qua market actor, translation is multiple: social problems are translated to market opportunities and market opportunities to engineering problems; research is translated into knowledges, knowledges into things, and things into commodities; applications into solutions; research projects into intellectual merits and broader impacts; and nanoengineering into social benefit. Whether benefit is articulated as technological progress and economic activity, as capital accumulation, or as the fulfillment of the nano dream, innovation for the benefit of society is implicitly understood as the ultimate result of these translational flows. The word "benefit" in fact includes two meanings, both of which are relevant here: "A thing well done; a good, or noble deed" and "Pecuniary advantage, profit, gain."[5]

Medical Origins and the Broader Discourses of Translational Research

The term "translational research" is a relatively recent development, and is primarily associated with medical research, connoting a "bench-to-bedside" translation of basic medical research into clinical applications to diagnose and treat disease in humans. The term rarely appeared in journal articles in the 1990s, and when it did, it had a narrowly circumscribed definition connected to cancer research.[6] Its uptake more broadly is connected to efforts by the National Institutes of Health (NIH) in the early to mid-2000s to more efficiently move basic laboratory research into areas of clinical application. In 2006, the NIH established the Clinical and Translational Science Awards Consortium with the goal of establishing fifty translational research centers nationally. Not long after this, in 2007, The *Journal of Laboratory and Clinical Medicine*—first established in 1915—was renamed to *Translational Research, The Journal of Laboratory and Clinical Medicine*.[7] Such a renaming suggests that if not a direct response to the NIH efforts, the term "translational research" was becoming widespread by the mid-2000s. And in 2009 two new journals were established: the *Science Translational Medicine*

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5. Oxford English Dictionary, *"Benefit, N."* [in English], Oxford University Press.

6. Rubio et al., Acad Med. 2010 Mar; 85(3): 470–475, doi: 10.1097/ACM.0b013e3181ccd618, p 470.

7. https://www.elsevier.com/journals/the-journal-of-laboratory-and-clinical-medicine/0022-2143, accessed January 24, 2016.

journal and the *American Journal of Translational Research*. In 2012, the NIH established the National Center for Advancing Translational Sciences (NCATS) to "transform the translational science process so that new treatments and cures for disease can be delivered to patients faster."[8] This signals a moment in which the research gaze turns inward toward its own processes with the goal of making them more efficient. Translational research becomes not just a moniker for a specific domain, but a mode of research governance; translational science codifies a set of best practices for speeding up innovation. NCATS defines the "translational community" as including "researchers, clinicians, regulators, patient and community groups, and industry,"[9] a broad group that speaks to the various actors involved in translating laboratory research into clinical application.

Most definitions of translational research still frame it explicitly in relation to medical research. NCATS defines it as "the process of turning observations in the laboratory, clinic and community into interventions that improve the health of individuals and the public—from diagnostics and therapeutics to medical procedures and behavioral changes."[10] The NIH further specifies in its grants glossary that translational research is comprised of two areas: applying discoveries from laboratory research and preclinical studies to clinical trials and studies with humans (T1), and conducting research to

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8. http://ncats.nih.gov/about/center accessed May 14, 2015.

9. Ibid.

10. http://ncats.nih.gov/translation accessed May 14, 2015.

enhance “the adoption of best practices in the community” (T2).[11] T1 translates *products* from lab to clinic, and T2 codifies best practices (*processes*) organized around these products. I highlight products and processes because, as I will soon discuss, these are the two components of innovation, as defined by economists. Many translational research centers refer to two additional areas of translation, identifying T2 as the codification of best practices, T3 as moving these best practices from clinic to broader community, and T4 as evaluating outcomes and/or drawing on these outcomes to formulate new policy research.[12]

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11. http://grants.nih.gov/grants/glossary.htm#TranslationalResearch accessed 5-14-2015.

12. See, for example, the University of Michigan Institute for Clinical and Health Research, the Tufts Clinical and Translational Science Institute, and the Clinical Science & Translational Research Institute of Southeast Wisconsin. https://ctsi.mcw.edu/community/what-is-translational-research, http://www.tuftsctsi.org/About-Us/What-is-Translational-Science.aspx, accessed May 14, 2015.

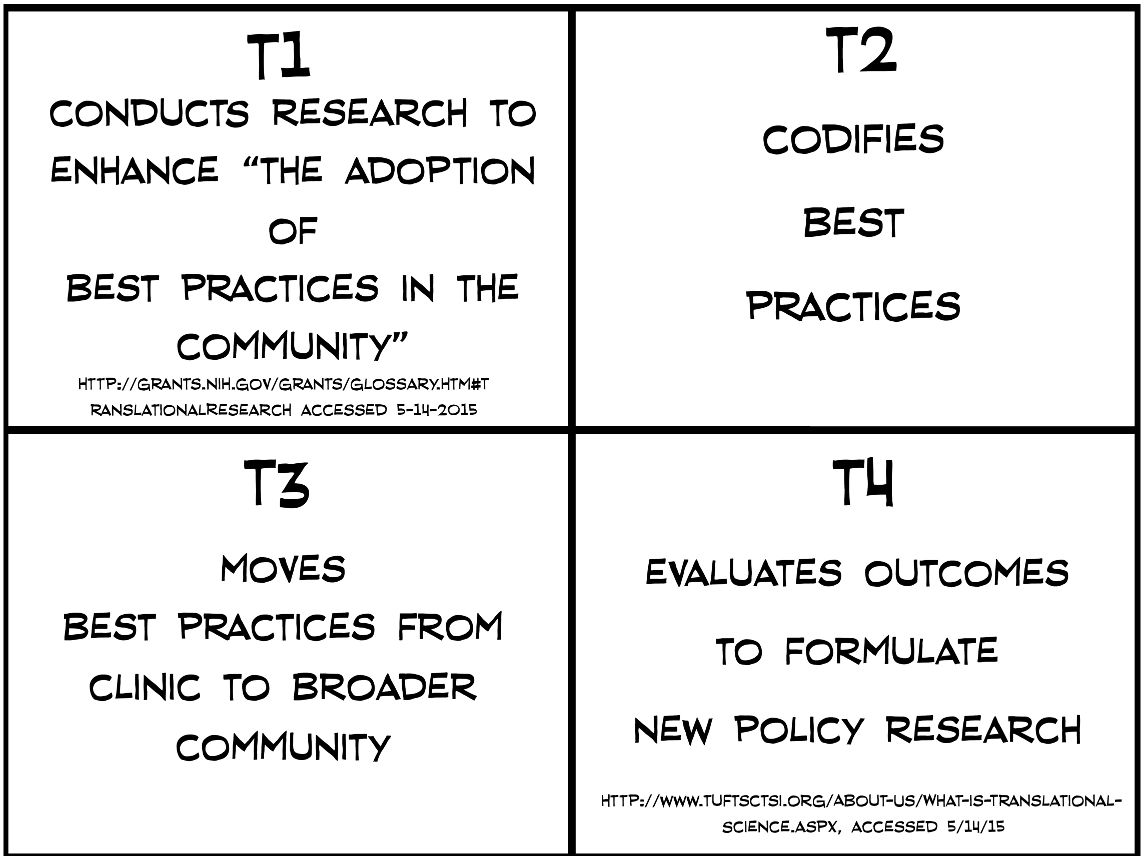

Illustration 121 T1 through T4.

The translational apparatus has two goals: to optimize innovation so that medical research quickly reaches patients, and to always be optimizing and propagating the best practices for doing this. Translational research is therefore a new yet highly articulated mode of knowledge production and governance: experiments in laboratories with nonhuman entities become experiments on humans; the knowledge abstracted from these experiments is codified and embedded into best practices; these best practices are disseminated, becoming the dominant mode of conduct in clinical and community settings organized around particular presentations of human disease, diagnoses, and therapeutics; and these best practices are further codified in local, state, and federal policies.

Definitions and descriptions of translational research frequently highlight themes of efficiency, speed, and usefulness. For example, with respect to speed, NCATS states that translational research aims to "reduce, remove or bypass costly and time-consuming bottlenecks in the translational research pipeline in an effort to speed the delivery of new drugs, diagnostics and medical devices to patients."[13] Efficiency is often highlighted, such as in the 2014 NNI Strategic Plan statement indicating that the White House has a "…cross-cutting desire to more efficiently move ideas from the lab to the market."[14] NCATS also describes translational research as a "team activity"[15] and as a mode of knowledge production that requires multiple skillsets.[16] These are attributes that are relevant for understanding its uptake in nanoengineering, as I will discuss.

Translational Research As a Paradigm of Innovation

I will examine first how translational research as a paradigm of innovation signifies a set of commitments and values that make it a good fit for nanoengineering in this department. As a label for nanoengineering research, it takes on the attributes established in the medical realm, but also figures translation more broadly. I will then

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13. http://ncats.nih/gov/about/center accessed May 14, 2015.

14. http://nano.gov/sites/default/files/pub_resource/2014_nni_strategic_plan.pdf 71 accessed June 11, 2015.

15. http://ncats.nih.gov/files/NCATS-factsheet.pdf.

16. http://moores.ucsd.edu/industryrelations/symposium.htm.

show specifically how translation, broadly construed, fits the identity of the nanoengineer.

Translation and Innovation

The department's claim that it does translational research should be understood alongside its claim that it is an innovation ecosystem. Setting aside for the moment the ways in which "ecosystem" naturalizes the activities of this department, I want to take the claim at face value and think of this innovation ecosystem as a translational apparatus. When economists talk about innovation, they define it in terms of products and processes introduced in the market place. Economists Christine Greenhalgh and Mark Rogers state that this introduction to the market place is necessary for something to count as innovation:

> The product or process must be introduced into the market place so that consumers or other firms can benefit. This distinguishes an innovation from an invention or discovery. An invention or discovery enhances the stock of knowledge, but it does not instantaneously arrive in the market place as a full-fledged novel product or process. Innovation occurs at the point of bringing to the commercial market new products and processes arising from applications of both existing and new knowledge.[17]

In the context of medicine, the need to bring the product or process to market is quite explicit: in the current political economy of pharmaceutical development, in order to move into clinical trial and from there to patients, a new diagnostic or therapeutic technology has to be produced by industry. As the Moores Cancer Center Translational Oncology Symposium states, "Represented will be many of the different skill sets needed to bring a new drug to market—from the lab, through the commercialization process to

17. Christine Greenhalgh and Mark Rogers, *Innovation, Intellectual Property, and Economic Growth*, Princeton: Princeton University Press, 2010, 5-6.

the patient's bedside."[18] Here, the significance of "to" in the shorthand "bench-to-bedside" is made explicit: it is commercialization. Translation, then, even in the context of cancer research, is a particular way of thinking about the commercialization of research and the return on investment.

This highlights an important fundament of translational research: to commercialize, something must be commodified. This is in line with an economic view of both knowledge and technology, which defines these terms in relation to commodification and production. Greenhalgh and Rogers provide these definitions from the field of economics:

> Economically relevant knowledge is the whole body of scientific evidence and human expertise that is, or could be, useful in the production and supply of commodities and in the invention and design of new products and processes…. Technology encompasses the current set of production techniques used to design, make, package, and deliver goods and services in the economy. So technology is the application of selected parts of the knowledge stock to production activity.[19]

Here, economically relevant knowledge must be useful in commodifying a product or process, that is, it must help constitute innovation. And technology must one way or another make these goods and services available through an economic transaction. In an innovation ecosystem conducting translational research, these economic definitions of knowledge and technology are the ones circulating. Knowledge must be, or promise to become, economically relevant, and the market place is the necessary destination for research products. Without being introduced into the market place, the department's

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18. http://moores.ucsd.edu/industry relations/symposium.html.

19. Greenhalgh and Rogers, *Innovation, Intellectual Property*, 6, emphasis original.

knowledge production would not translate to innovation, and there would be no intellectual capital.

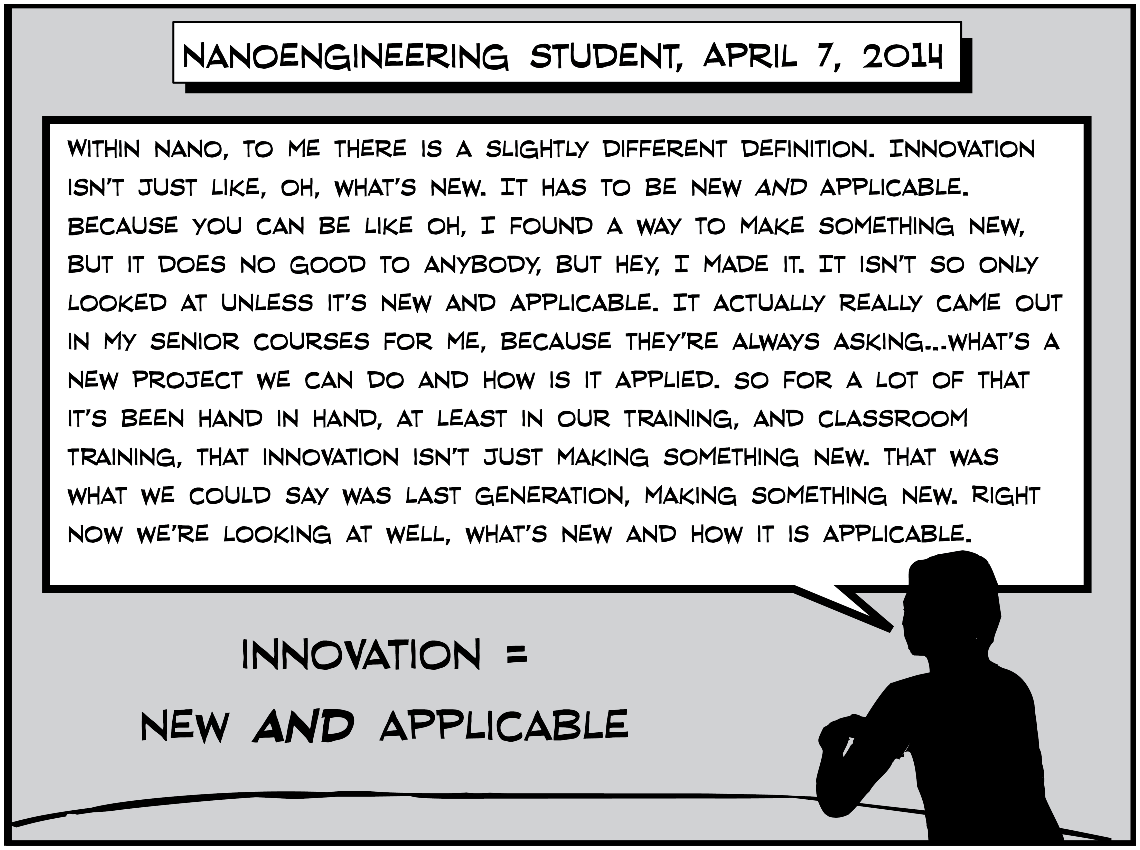

Illustration 122 Innovation means new *and* applicable. This fourth-year nanoengineering student stresses the necessity of applicability for something to count as innovation in the context of nanoengineering. Applicability is usually associated with commercialization, or translation to the market place.

Moreover, it is only through translation to the market place that what the department produces can be used by people. In Chapter 5, I quoted the chair of the department telling students, "We are a department really committed to translational research. We want the stuff that we do to go out and be used by people."[20] The social benefit that nanoengineering promises is only realized when products are used by people.

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20. Chair lecturing to students in Intro I, 2011, transcribed by the author.

The ways in which translational research unites utopia and utility—aligning the possibility of progress and value for human lives with the necessities of efficient production and marketization so that products are useful—make it an appealing category for nanoengineering.

I will analyze this in more detail, but first I want to briefly demonstrate that it is not just in the department that translation is taken up to describe nanoengineering research. For example, the NNI strategic plans routinely describe nanoengineering as translational research. The 2011 plan states that the NSF "…advances nanotechnology innovation through a variety of translational research programs and by partners with industry, states, and other agencies."[21] The Budget Supplement of this plan states that one of its goals is to "Foster the transfer of new technologies into products for commercial and public benefit" and indicates that the NSF supports this goal by:

> Strengthening the contribution of translational innovation programs from fundamental research, including in Grant Opportunities for Academic Liaison with Industry (GOALI), Partnerships for Innovation (PFI), and Industry-University Cooperative Research Centers (IUCRC).[22]

In these statements translation connotes a mode of doing research that is oriented toward innovation and commercialization for public benefit and that achieves this through partnerships between university, industry, and state. Utility is also a key theme. For example, the 2010 President's Council of Advisors on Science and Technology (PCAST) report for nanotechnology states that "The NNI can help promote successful

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21. 2011 National Nanotechnology Initiative Strategic Plan, http://www.nano.gov/node/581, 19, accessed 06/29/2015.

22. Ibid., 40.

commercialization by supporting applied and translational research on the integration of nanoscale materials and devices into useful products…" and later suggests that the NNI could "include setting goals such as creating low-cost solar cells…to spur applied and translational research directed toward those applications."[23] Here translation is not only connected to commercialization but again toward "useful products" that can be directed toward particular types of applications. It is not clear why "applied" and "translational" are invoked, implicitly suggesting a distinction between the two. I surmise this is partially due to the relative newness of translational as a handle for this type of research, and partially because translational is actually a larger category that includes but exceeds applied research. I will discuss this further below.

So while translational research has its origins in the medical field, and is still largely associated with medicine, it is now clearly being taken up in the field of nanoengineering. But why does nanoengineering—which includes but exceeds medically relevant research—claim to be translational? What does this achieve that isn't already accomplished by the term "innovation"? Most obviously, placing all of nanoengineering research under the umbrella of translational research—with its medical association and promise to save lives—may borrow from the moral authority of medicine and support the nano dream imaginary of saving lives and benefitting humanity. But I argue that translation does more interesting work besides. In analyzing the consolidation of nanoengineering as innovation for the benefit of society, I have focused on how the nano

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23. President's Council of Advisors on Science and Technology Report, https://www.whitehouse.gov/sites/default/files/microsites/ostp/pcast-nni-report.pdf, 20, 30, accessed June 29, 2015.

dream helps to establish the utopian horizon of research, and how the nanoscale demarcates a unique domain for innovation (in Chapters 2 and 3, respectively). Translational research organizes how this innovation is approached and achieved within the larger political economy of nanoengineering. It marks the path from the nano world to the nano dream, a path that necessarily passes through the market place and that ideally constitutes the most direct route between science and society. I will briefly outline my key points about how and why translation is taken up in this space, and then elaborate on each.

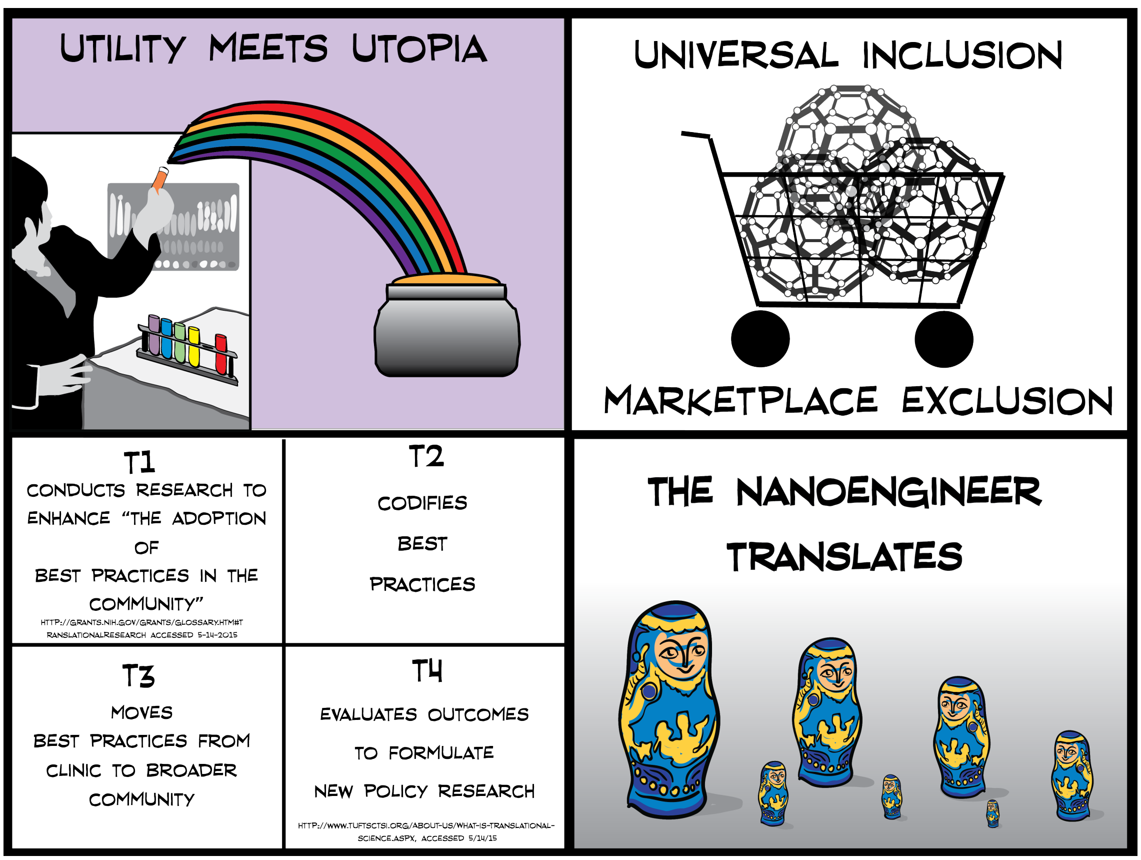

Illustration 123 Translational research.

First, as I've already suggested, it unites the utopian possibilities of technological progress and societal benefit with the utilitarian imperative to innovate efficiently and produce things that will be used by people. Key to this is locating all aspects of the research process within the continuum of translation toward the market place. Second, it works to align the privatization of knowledge with the promise of public benefit that is usually associated with public goods. Relatedly, it operates within a discursive arena of universal inclusion while necessitating a market logic that predicates value on exclusion. Third, it signals a form of governance for research practice, and positions the market as the information processor that mediates the activities of state, university, industry, and citizen, as part of this translational apparatus. Social problems are translated into market opportunities, and engineering solutions into valued commodities. The translational apparatus maintains the "communistic fiction" of one society and one interest through these translations.[24] Finally, it positions the nanoengineer as the translator who, through her multiple translations, unites utopia with utility. This last point provides some possibility for intervention. The nanoengineer as a translator is a key political-economic actor central to the translational apparatus, an agent of meaning-making in these translations. Her mode of knowledge production is one that highlights the contingent and social character of the knowledge she produces. And, while in the domains of both medicine and nanoengineering translation is usually conceptualized in one direction—from bench to bedside, or from lab to society—because the marketplace is figured as the mediator between science and society, or the "to" in "bench-to-bedside," STS may be

24. Hannah Arendt, *The Human Condition*, 2nd ed. Chicago: University of Chicago Press, 1998, 43-4. Arendt is citing Gunnar Myrdal when she says it was the liberal economists "who had to introduce the 'communistic fiction', that is, to assume that there is one interest of society as a whole which with 'an invisible hand' guides the behavior of men and produces the harmony of their conflicting interests" (44).

able to use the handle of translational research to highlight the other direction—bedside-to-bench and society-to-lab.

The Translational Continuum

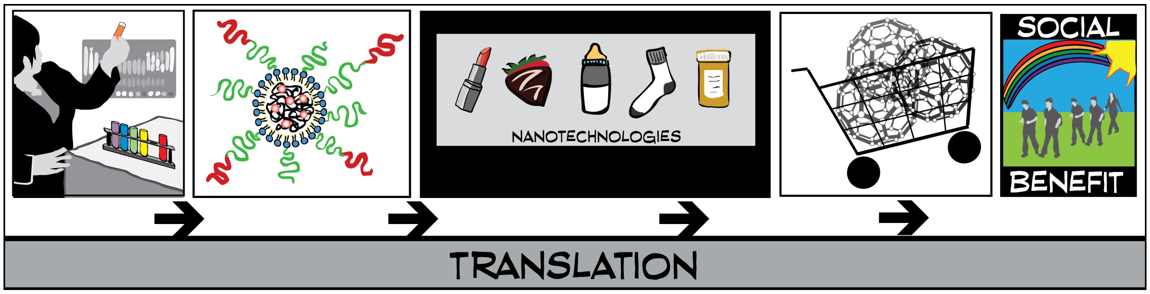

Illustration 124 The translational continuum.

Within an ethos of translational research, all research, however basic, must be conceptualized as part of a continuum of knowledge production that is moving toward the market. Scientists and engineers may engage in fundamental and theoretical work, but it must be done in a context of application.[25] For example, in a funding application, a faculty principal investigator (PI) in my site writes:

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25. Michael Gibbons, Camille Limoges, Helga Nowotny, and Simon Schwartzman, *The New Production of Knowledge : The Dynamics of Science and Research in Contemporary Societies*, London ; Thousand Oaks, Calif.: SAGE Publications, 1994. While "context of application" might suggest that this fits in with Mode 2 knowledge production described by Gibbons et al., it is not an exact match. First, Mode 2 characterize context of application as problem solving organized around a particular application than around a particular discipline, describing this knowledge production as transdisciplinary (Gibbons, et al., 1996: 3). But with nanoengineering, you have a new disciplinary formation that is itself transdisciplinary, and research in the department is both organized around a particular application and around a discipline, such as it is. Second, the imperative of usefulness is always present in Mode 2 knowledge production and various interests are involved. This applies in the work of the nanoengineers in this department, as well. However, the authors describe Mode 2 as product development that is not directly *for* industry or markets but that is instead informed by supply and demand factors in ways that are "…much broader than what is normally implied when one speaks about taking ideas to the marketplace" and "because they include much more than commercial considerations, it might be said that in Mode 2 science has gone beyond the market!" (Gibbons et al., 1996: 4). It is not clear to me how markets can be distinguished from supply and demand factors, but I do not think that the research program in this department can be said to go "beyond the market". While I think many nanoengineers are driven by interests that exceed market or commercial

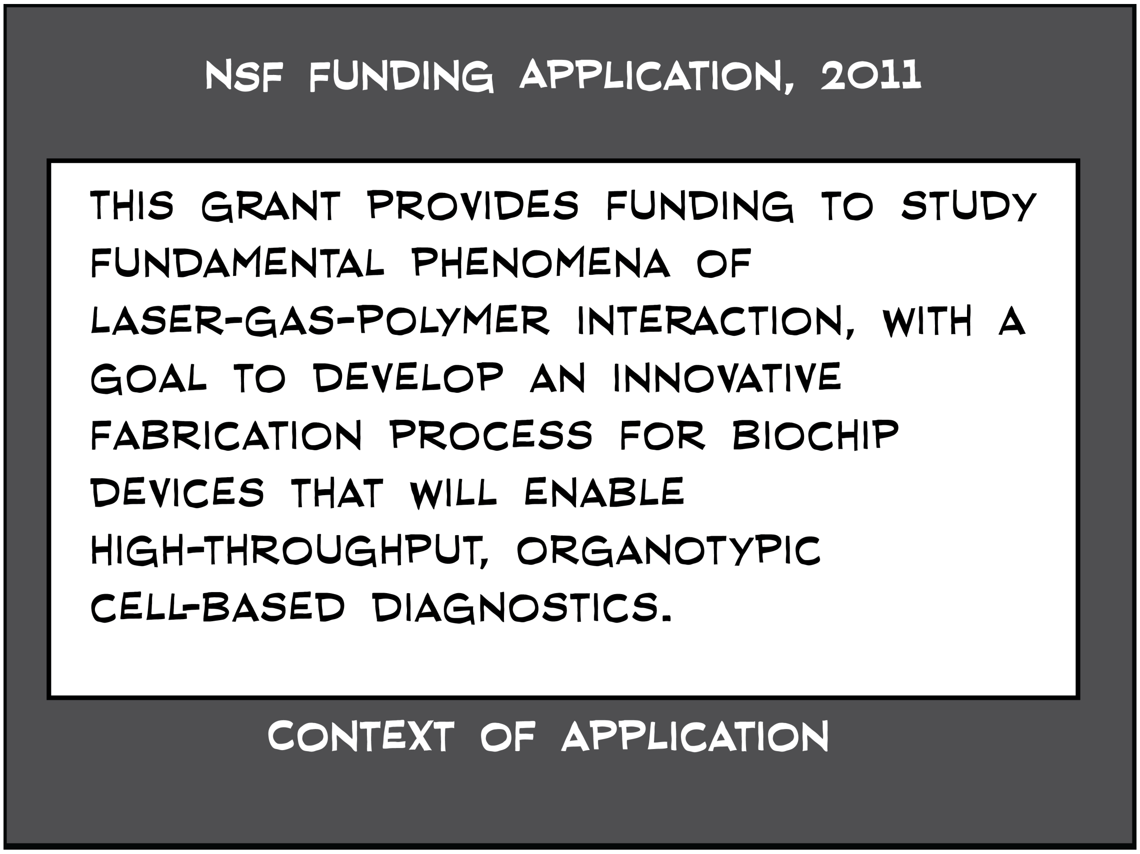

Illustration 125 Fundamental work in a context of application. "This grant provides funding to study fundamental phenomena of laser-gas-polymer interaction, with a goal to develop an innovative fabrication process for biochip devices that will enable high-throughput, organotypic cell-based diagnostics."[26]

The "fundamental phenomena" that are being researched are nevertheless explicitly linked to the context of application, in this case potential diagnostic applications. This helps to explain how this nanoengineering department sees nanoengineering as doing both science and engineering, both fundamental and applied work. Additionally, as I previously mentioned, faculty are often engaged in a range of projects spanning the

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interests, when a project is initiated, it must accord with market constraints. At this point, it seems a distinction without a difference to suggest that knowledge production is not *for* the market.

26. Principal Investigator, National Science Foundation funding application (NSF: CMMI), September 1, 2011.

translational continuum. For example, one faculty PI indicated that she had two different projects related to energy storage:

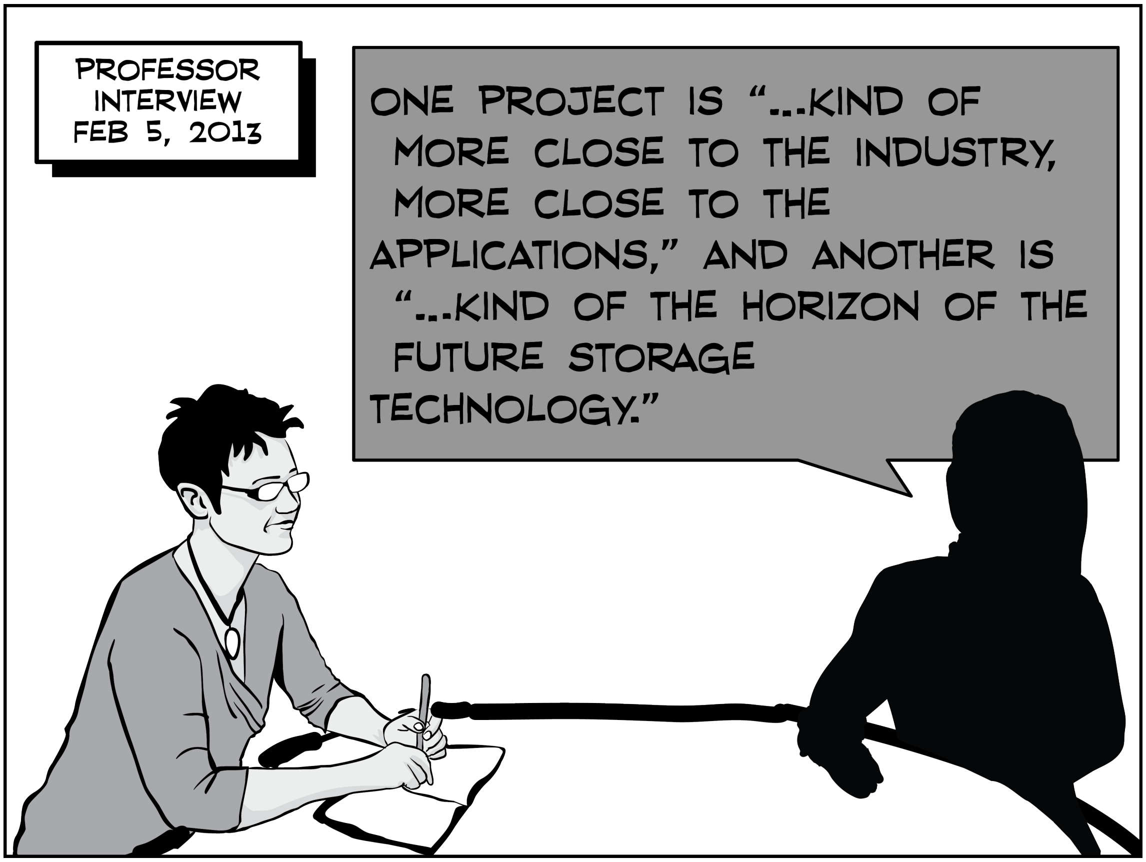

Illustration 126 Interview with NanoEngineering professor. One project is "…kind of more close to the industry, more close to the applications," and another for which no market yet exists because it is "…kind of the horizon of the future storage technology."[27]

Here, both projects are in the context of the same application domain, but they are situated differently along the translational continuum, *i.e.* with respect to the market.

This doesn't mean that nanoengineers are only interested in fundamental research for its potential to translate, only that they must conduct research within this translational

27. Interview with NanoEngineering professor, February 5, 2013, transcribed by author.

framework. For example, one faculty PI described his motivation in pursuing a fundamental research question in non-utilitarian terms:

> We need to know how it works. Just from a basic fundamental perspective, I mean, wouldn't you want to know? Wouldn't you want to know how your brain functions? Forget medical reasons, and mental this and control and all those things, but wouldn't you want to understand how something works? Just from that…point of view.[28]

Here, the professor indicates intellectual curiosity is driving his research, aside from potential applications. While the political economy of working in a translational discipline requires the faculty to orient their work toward the market, this is not mutually exclusive with genuine curiosity that is often associated with what is usually labeled "basic" research. Nevertheless, as in the cited funding application, even fundamental research must be able to articulate the application on the horizon.

Translation As **Translatus**

The word translation, coming from the Latin *translatus*, or "carried over," signals a movement from one medium to another, where that which moves is ostensibly the same. With languages, when a word is untranslatable from one language to another it is because no concept carries the same or sufficiently proximate meaning, therefore the meaning cannot be carried over into this new language. Does this sense of something being carried over, or a movement between different media, apply to translational research? Consider the language of Holden Thorp and Buck Goldstein—former chancellor and economics professor, respectively, of the University of North Carolina Chapel Hill—in discussing the cultural requirements for a university to support enterprise

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28. Interview with NanoEngineering professor, March 1, 2013, transcribed by author.

creation. They argue that "what we call the 'translational disciplines' are key to encouraging a culture and a conversation that leads to enterprise creation," and they define a translational discipline as one that "straddles the border between academia and the outside world."[29] They further elaborate:

> Faculty from translational disciplines often spend time each week engaged in enterprises outside the academy. The curricula teach hard skills, and professors and practitioners work together to prepare students for professional work. Internships and other forms of experiential learning are encouraged. These disciplines apply academic knowledge to real-world problems with an eye toward the customers, patients, clients, and readers who will ultimately help determine success. The most obvious example of a translational discipline is engineering.[30]

In this discussion of translational disciplines, the authors describe faculty and students moving between academy and industry, as well as a movement of knowledge between academy and the "real world." Through translational disciplines in an entrepreneurial university people and knowledge are conceptualized as moving from university to enterprise.[31] Although, in considering my analysis in Chapter 5 of how the ideal university graduate is mutually articulated by university, industry, and state, we should expect that with translational research, the movements of translation are actually multiple and multi-directional. Nevertheless, in the 21st century language of the entrepreneurial university, translational research is discursively connected to a movement toward the

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29. Holden Thorp and Buck Goldstein, *Engines of Innovation : The Entrepreneurial University in the Twenty-First Century*, Chapel Hill: University of North Carolina Press, 2010, 44.

30. Ibid., 44-5.

31. Oxford English Dictionary, *"Enterprise, N."* [in English]. Oxford University Press. The term 'enterprise' comes from the French entreprendre, to "undertake, take in hand." The movement from academy to the enterprise is metaphorically one from head to hand. This is apt for a mode of knowledge production that emphasizes utility.

outside—toward enterprise creation, the real world, the applications that will be made, and the market. Translational research connotes the material, semiotic, and economic transformations associated with the movement of knowledge and knowledge workers—both articulated as capital—that secure the commodification of knowledge production.

But translation is at once abstract and multi-purpose, broadly signifying that value is generated in the process of something being carried over toward the market place and toward usefulness even if enterprise creation and commodification are not explicitly referenced. For example, one faculty PI in the department used the term "translation" to indicate that his research was ready to move from pre-clinical animal studies to the next phase: "The next step is really to translate this one to human tests…so the next step is we want to bring these to human tests."[32] Here "translate" is used in this etymological sense of carrying over, or in this case "bringing to," and it signals some movement from bench to bedside. Another faculty PI used the term translation to signal the interpretive functionality of an instrument he is creating:

> We do make a lot of these devices and materials that could be useful for biomedical applications…it could be I guess drug delivery, just understanding how strong drugs interact with different cells, or different chemicals within the body and things like that…. So with our system we actually think we can translate this, because it's very sensitive, to measure single bond strengths, like single molecule bond strengths at a very very high throughput [..]. So we can literally screen sort of what chemical you may want to put on the outside of that drug or attach to the drug.[33]

Here problems are framed in terms of an application domain (biomedical applications), and the nanoengineer indicates that the instrument he is developing will be able to

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32. Interview with NanoEngineering professor, November 27, 2012, transcribed by author.

33. Interview with NanoEngineering professor, March 14, 2013, transcribed by author.

translate measurements of single bond strength into data that will guide drug design. At the same time, he also translates between problem and solution and recalls the ultimate utility of this translation insofar as the new instrument could be useful for biomedical applications. Translation constitutes a set of movements and exchanges that produce value—economic value, but also utility and benefit more broadly.

Usefulness and Efficiency

Translation fits with the department's emphasis on utility, and underscores the efficiency of the practices of innovation. Utility is particularly emphasized in contexts outside of medicine, perhaps because within medicine it is assumed. In the dean's 2011 welcome speech previously referenced in Chapter 5, recall that he said to students:

> And if our research in the end does not get translated to industry, to practice, if it just ends up on the shelf, then we are doing something wrong. So this is the intellectual capital we should be creating as a research engineering school.… We are educating tomorrow's technology leaders…. And there should be a reason for you to come [here]…, mainly to participate in research, even as an undergraduate… and then transfer our discoveries for the benefit of society. This is what engineering is all about.[34]

Here translation happens *to* industry and *to* practice (echoing the product and process components of innovation), and is contrasted with something that would end up on the shelf, unused. Translational research is then linked to transferring discoveries to society and societal benefit, paralleling the bench-to-bedside descriptor of translational research in medicine. Rather than bench-to-bed, it is lab-to-society, but the "to" stands for

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34. Dean, Admit Day Speech, April 9, 2011, observed and transcribed by author, emphasis added.

commercialization in both cases. Rather than promising life, as in the case of medicine, it is usefulness that is necessary to secure benefit.

Likewise, recall that the department's commitment to translational research is connected to the idea of utility:

Illustration 127 "We want the stuff that we do to go out and be used by people."[35]

The department's research products must be "used by people" to achieve the goal of translational research. This is echoed outside the department in the 2010 PCAST report:

> The NNI can help promote successful commercialization by supporting applied and translational research on the integration of nanoscale materials and devices into useful products—incorporating carbon nanotubes into

35. Chair of the department, Intro I, January 11, 2012, observe and transcribed by the author.

> composite materials or optimizing biohazard sensors for performance in battlefield environments, for example.[36]

In order to achieve this usefulness, research must be transferred to industry, or commercialized, and from industry to society in the form of "useful" products. Societal benefit and usefulness are implicitly equated. This ideal of usefulness becomes the content of social benefit. Yet when utility itself becomes the end, as Hannah Arendt suggests, there is no prior principle that justifies it:

> It is "for the sake of" usefulness in general that *homo faber* judges and does everything in terms of "in order to." The ideal of usefulness itself, like the ideals of other societies, can no longer be conceived as something needed in order to have something else; it simply defies questioning about its own use….The perplexity of utilitarianism is that it gets caught in the unending chain of means and ends without ever arriving at some principle which could justify the category of means and end, that is, of utility itself. The "in order to" has become the content of the "for the sake of"; in other words, utility established as meaning generates meaninglessness.[37]

Who will use a technology, how it will be used, or what consequences there might be to such use are structurally less relevant than the fact of its usefulness. In this sense, translational research does more than unite utopia and utility; it understands utopia in fundamentally utilitarian terms. Benefit is secured when something is used, which is understood as something that can only happen when research products pass through the market place. Consumption implies usefulness and consequently indexes benefit.

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36. President Council of Advisors on Science and Technology, 2010 Report, March 12, 2010, 29.

37. Arendt, *The Human Condition*, 154.

The Economic Register of Public and Private Goods

By orienting all research toward the market place, translation organizes scientific activity as economic conduct, and frames that economic conduct as the means of producing social benefit. This could be articulated as producing public goods through private means. Yet, as Philip Mirowski points out, defending against the commercialization of science by appealing to the idea that science is a "public good" fails to take into account the ways in which the very notion of a public good emerged in postwar neoclassical economic theory in the 1950s.[38] Let me back up. In economic terms, at least since the 1950s, something is considered a public good if it is nonrival and nonexcludable. Nonrival means that "any single use of the public good does not affect its availability to other users" and nonexcludable means that "its use by one party still implies access for all, which cannot easily be blocked."[39] Regarding basic research, Greenhalgh and Rogers write:

> Basic research has more the nature of a *public good* because its applications can be in different fields (and diverse applications are nonrival)…. Also, once a scientific discovery is made it is hard to suppress it or keep it secret, so basic scientific knowledge is also more likely to be nonexcludable. In contrast, a firm undertaking near-market applied R&D and introducing a specific innovation is closer to supplying a private good with externalities."[40]

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38. Philip Mirowski, *Science-Mart : Privatizing American Science*, Cambridge, Mass.: Harvard University Press, 2011, 56-7.

39. Ibid., 18. So for example, a public park is nonrival because its use by one person doesn't make it less available to be used by another, whereas an ice cream cone once consumed by one person is no long available to others. A street light is nonrival because it would be impractical to try to exclude any particular person from enjoying its benefit, even if they didn't pay for it. A premium cable channel subscription is rival.

40. Greenhalgh and Rogers, *Innovation, Intellectual Property*, 20.

According to these economic terms, faculty in this department who publish new knowledge in academic journals, for example, render that knowledge nonrival and nonexcludable, or public.[41] However, their success as nanoengineers in the Jacobs School also depends on their participation in the broader mission of innovating for the benefit of society, which is to say, bringing their translational research into the market place and producing intellectual capital. Therefore faculty must also produce knowledge as a private good, making it excludable and rival—and thus definitionally not universally available—by commodifying it through patenting, licensing, enrolling corporate partners, and starting their own companies. Through the excludability of knowledge and through exclusions intrinsic to the market place within capitalism—namely the exclusion of those persons or firms who cannot pay the price—benefit in these economic terms must necessarily have a more circumscribed recipient than society at large.

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41. Michel Callon, "Is Science a Public Good? Fifth Mullins Lecture, Virginia Polytechnic Institute, 23 March 1993," *Science, Technology & Human Values* 19, no. 4 (October 1, 1994): 395-424. See Callon for a vigorous rejection of the assumptions economists make in designating knowledge a public good. Callon argues that economists' understanding of knowledge in terms of information is misguided, and that there is nothing intrinsic to science that would make it difficult to commodify.

Illustration 128 Universal inclusion, marketplace exclusion.

Producing knowledge that is rendered private through patenting, corporate agreements, military classification, and other mechanisms, is not a new phenomenon for scientists and engineers or for the research university, as I touched on in Chapter 5. And certainly the commodification of knowledge did not begin with the translational paradigm. What is notable in terms of how nanoengineering is being consolidated as an intrinsically ethical identity serving society, and the ways in which it is being articulated as translational research, is that the status of knowledge as a public or private good is seemingly irrelevant to this project. Within a broader set of discourses in which the private sector is regarded as the source of innovation and social and economic benefit, the idea that public benefit is primarily secured through private acts is a commonplace. As part of translating nanoengineering research into the benefit of society, nanoengineers fluently translate exclusive private goods semiotically to inclusive public good. This is achieved in part through promissory visioning and broader impact statements, which I will return to. This translation—hardly exclusive to the domain of nanoengineering—is made seamless in several ways: first, by the widespread assumption that the private sector, and high-tech innovation in particular, is a primary means of securing social and economic benefit; second, by the fact that as part of the translational continuum, research is not demarcated as basic or applied, public or private; and third, and relatedly, nanoengineers emphasize *doing* public good—articulated as social benefit, secured through innovation—rather than producing private or public goods, as defined by economists.

So while knowledge is considered intrinsically nonrival by economists—more than one person can use knowledge without devaluing it or making it harder for another to use it—in a knowledge economy with an intellectual property regime, knowledge can and often is made rival, by these same terms. While commercialization and privatization of knowledge are not new phenomena in science, and particularly in engineering, the assumptions of translational research are nevertheless notably different from those Vannevar Bush laid out in his famous report to the President in 1945, *Science, the Endless Frontier*. In it, Bush discussed capital, but this was not intellectual capital that signaled the achievement of commercialization. Instead, he talked about scientific capital, which he defined as the basic scientific research that provided the "new principles and new conceptions" that become the foundation from which new products and processes (*i.e.*, innovation) are born.[42] This basic scientific research importantly needed to be conducted in an environment that was protected from the needs of commercialization:

> Publicly and privately supported colleges and universities and the endowed research institutes must furnish both the new scientific knowledge and the trained research workers. These institutions are uniquely qualified by tradition and by their special characteristics to carry on basic research. They are charged with the responsibility of conserving the knowledge accumulated by the past, imparting that knowledge to students, and contributing new knowledge of all kinds. *It is chiefly in these institutions that scientists may work in an atmosphere which is relatively free from the adverse pressure of convention, prejudice, or commercial necessity.* At their best they provide the scientific worker with a strong sense of solidarity and security, as well as a substantial degree of personal intellectual freedom. All of these factors are of great importance in the development of new knowledge, since much of new knowledge is certain to arouse opposition because of its tendency to challenge current beliefs or practice.
>
> *Industry is generally inhibited by preconceived goals, by its own clearly defined standards, and by the constant pressure of commercial necessity. Satisfactory progress in basic science seldom occurs under conditions prevailing in the normal industrial laboratory*.[43]

Bush argued that innovation depended on basic research, and that basic research depended on an environment free from commercial pressures. By contrast, translational research posits that innovation is most efficiently and effectively achieved when its concrete materialization, which must necessarily occur through commercialization, is clearly within view even at the earliest stages of research. Thus one doctor in an editorial bemoans the ways in which "every grant application to the NIH must now be evaluated

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42. Vannevar Bush, *Science, the Endless Frontier*, A Report to the President, July 1945, https://www.nsf.gov/od/lpa/nsf50/vbush1945.htm - summary, accessed January 29, 2016, emphasis added.

43. Ibid.

on its practical merits, as if an obvious practical application is an essential requirement of all research."[44] He goes on to claim that this is threatening basic science:

> In the current enthusiasm for translational research, we must not forget that basic science is under threat. Medically related basic science research is particularly vulnerable because the NIH is the only source of support for much of this work, whereas applied research may be supported by a mixture of government, commercial, and private foundational sources. Moreover, over the past 2 decades industry has replaced the federal government as the leading source of support for research and development (Fig. 1). Funding trends have shown flat federal support for basic science for more than 5 years (7) (Fig. 2A…. Until the pendulum swings and basic science reemerges as a national priority, *basic scientists will have to be imaginative in promoting the potential translational applications of their research*, develop new methods to "humanize" their work (10), integrate their basic studies as components of larger translational programs, and hope that study sections will continue to support good science even when it is not immediately apparent what the practical applications will be.[45]

This doctor suggests that the NIH funding applicant must be "imaginative" in order to articulate the potential practical applications that might emerge from one's basic research. Though outside the nanoengineering context, this suggests that at least some researchers see a danger in folding all knowledge production into the translational continuum. However, it also suggests that basic research is still being done. And, as I suggested, in some cases in the NanoEngineering department it may even be protected by not being labeled "basic" even if it requires a certain amount of translational work to articulate the practical applications it might ultimately support, and even if it must occur alongside research projects that can be more quickly marketized.

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44. http://enhancing-peer-review.nih.gov, accessed June 29, 2015, emphasis added.

45. Ibid., 564-5, emphasis added.

Concerns about funding aside, basic research—whether potential applications are identified or not—does not exist in some hallowed space just because it is further from marketization. Returning to Mirowski's point, the idea of basic research as a public good is not an entirely innocent one. Mirowski outlines the history of the idea of knowledge as a public good, showing that it was taken up by economists associated with the RAND corporation in the 1950s.[46] The concept was first articulated by Paul Samuelson in 1954 to reconcile government intervention with a free market ideology. As Mirowski notes, "[Samuelson] conceived it to formally justify the economic legitimacy of government intervention in the economy while still pledging allegiance to the iconic neoclassical model of the free market."[47] That is, Samuelson was trying to justify government investments into certain sectors without abandoning his commitment to the free market, and he did this by arguing that some things were public goods—like a police force, and knowledge—with intrinsic properties such that they couldn't be totally marketized. Citing David Hounshell, Mirowski further indicates that attempts to apply the concept of a public good to knowledge were particularly associated with defenses of a postwar government subsidy of science in the United States:

> These major proponents of neoclassical market models of science were part of a group of economists primarily associated with RAND, the Air Force think tank during that era. It was they who introduced the now-pervasive habit of treating the genesis of scientific knowledge as if it were production of a 'thing,' on a par with any other commodity, except for the fact that basic science was said to exhibit the characteristics of a public good. In other words, it was they who reified science as a conflation of

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46. Mirowski, *Science Mart*, 58.

47. Ibid., 57.

> object and process as a prelude to encompassing it as a subject of economic analysis.[48]

He argues that the subtext of the debates at RAND was a “dispute over whether there really could exist a rational science of war. The systems analysts at RAND believed not only could they plan an efficient war, but they could also create the advanced weapons systems need to prosecute it.”[49] Believing that the need for advanced weapons couldn’t wait for the market place, they argued that the military should control this research and development. Yet the neoliberal economists rejected the notion of knowledge as a public good, arguing that “all knowledge was always and everywhere adequately organized and allocated by markets.”[50] Incidentally, Alan Goolsbee, who later became the chair of President Obama’s Council of Economic Advisors, was one of the economists who argued against government funding of R&D.[51]

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48. Ibid., 58.

49. Ibid., 60.

50. Ibid., 61.

51. Ibid.

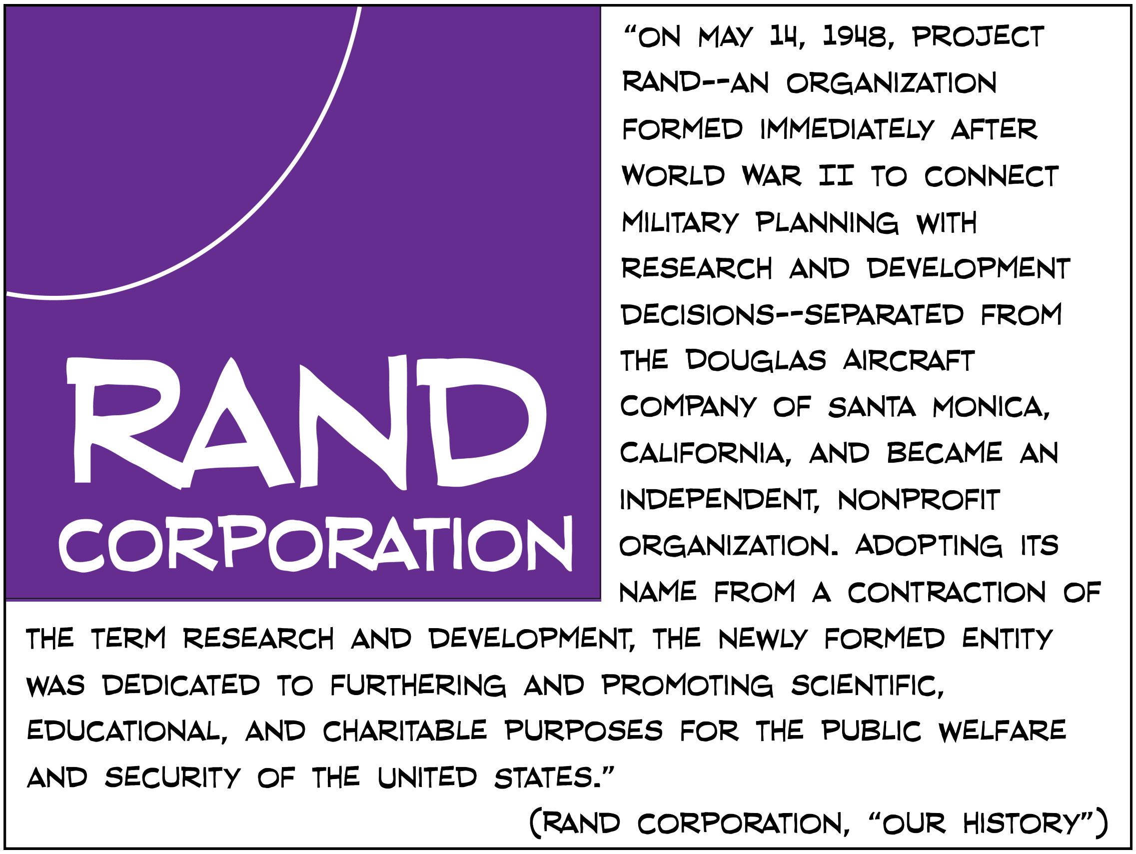

Illustration 129 Rand Corporation. "On May 14, 1948, Project RAND—an organization formed immediately after World War II to connect military planning with research and development decisions—separated from the Douglas Aircraft Company of Santa Monica, California, and became an independent, nonprofit organization. Adopting its name from a contraction of the term research and development, the newly formed entity was dedicated to furthering and promoting scientific, educational, and charitable purposes for the public welfare and security of the United States." (http://www.rand.org/about/history.html, accessed March 3, 2016).

Translational research organizes knowledge production as economic conduct, then, but this is not to say that the privatization of knowledge is new or that the antidote to commercialization is to recover the idea that knowledge is or should be a public good, at least not a public good as economists define it. In this vein, Michel Callon argues that science *is* a public good, but not because it is nonrival and nonexcludable, as economists would have it:

> Scientific knowledge does not constitute a public good as defined in economic theory. The private or nonprivate nature of science is not an

> intrinsic property. Degrees of appropriability and of rivalry are the outcome of the strategic configurations of the relevant actors, of the investments that they have already made or are thinking of making.[52]

Identifying the main result of scientific activity as the reconfiguration of heterogeneous networks[53], he argues that science is a public good when it increases diversity, when there is free association and circulation of the participants who are conducting research, when there is freedom to extend this collective, and when activities that would reduce variety (for example, of commodities) are suppressed.[54] I think the attention here to the diversity of human and nonhuman actors that participate in knowledge production and to the ways that knowledge production "causes new states of the world to proliferate"[55] goes a long way toward a redefinition of "public good" that is substantively different from that of the economists. However, it stays within an economic register, focusing more on the challenges of path dependency—when early market advantages make it increasingly impossible to marketize alternatives, as exemplified by the QWERTY keyboard—than on the political questions implicitly raised by his attention to diversity.

Translational research, as I've said, absorbs the categories of private and public goods, and basic and applied research, into it. Rather than an economic good that is nonrival and nonexcludable, translational research articulates public good in the abstract, in terms of social benefit guaranteed through innovation that is made possible through the

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52. Callon, *Is Science a Public Good?* 407.

53. Ibid., 411.

54. Ibid., 417.

55. Ibid., 418.

market place. To contest this adequately I think requires more than championing knowledge as a public good, even if public good is redefined in terms of diversity and flexibility rather than rivalry and excludability. Nor can it be adequately contested by championing basic research as opposed to applied—this would be to stay within the economic terms that focus on how, when, and what portion of knowledge can be commodified. Rather, by championing the idea of knowledge production as political conduct, different kinds of problems might be foregrounded. Rather then the problems of commodification, the problems of how a democracy imagines and contests progress, and who is included in these imaginaries comes to the fore. Certainly Callon's attention to the diversity of who produces knowledge is part of addressing this political problem. But rather than referring to the market to identify good problems or feasible solutions, political conduct might begin with questions of justice, equality, democracy, and collective political work to consider what might constitute social benefit, and for whom.

Translation as Governance

T1	T2	T3	T4
CONDUCTS RESEARCH TO ENHANCE "THE ADOPTION OF BEST PRACTICES IN THE COMMUNITY" HTTP://GRANTS.NIH.GOV/GRANTS/GLOSSARY.HTM#TRANSLATIONALRESEARCH ACCESSED 5-14-2015	CODIFIES BEST PRACTICES	MOVES BEST PRACTICES FROM CLINIC TO BROADER COMMUNITY	EVALUATES OUTCOMES TO FORMULATE NEW POLICY RESEARCH

Illustration 130 T1 through T4.

Translation also signals a form of governance for research and development by articulating the terms and best practices within which R&D must be conducted. Recall in my discussion of translational research in the medical domain that it is usually codified in terms of T1 and T2, with T2 specifically focused on research that supports identifying and propagating best practices throughout a research community. While the T1-T4 identifiers are not explicitly invoked in nanoengineering's uptake of translational research, the paradigm of translational research nevertheless focuses on the parameters within which R&D optimally moves from lab to society. By governance, I am drawing on Wendy Brown's analysis of governance as the "political modality through which [neoliberalism] creates environments, structures constraints and incentives, and hence conducts subjects."[56] She further describes it as focusing on tools and instruments for achieving ends, as supporting public-private partnerships, and as replacing "hierarchical, top-down mandates and enforcement with horizontal networks of invested stakeholders pursuing a common end."[57] Accordingly, translational research orients each actor toward the common goal of commodifying knowledge, without dictating the terms of specific research projects. Each actor—in this case a faculty member with her own lab who serves as a principal investigator on her research projects—selects her own research projects, dictates her research trajectory, and pursues funding and collaboration partners according to her own goals. The norms and best practices of translational research guide her to orient each of her research projects toward the market, to articulate the utility and utopian horizon of her research trajectory, to maintain multiple ongoing projects with more fundamental or theoretical research balanced by research that can be quickly marketized, and to pursue corporate partnerships as well as federal funding. Her tools and instruments include both publication and intellectual property regimes, university contract and

56. Brown, *Undoing the Demos*, 122.

57. Ibid., 126.

technology transfer offices, shared laboratory equipment as well as private and corporate-donated equipment, and affordable and free labor in the form of post-doctoral researchers, graduate students, and undergraduate students. Her success as a nanoengineer in this department does not hinge on following top-down directives from an authority figure. Rather, like a CEO of a small startup—a common comparison made in this innovation ecosystem—her success depends on her ability to secure investment in her research, and to independently and effectively produce human and intellectual capital.

The Nanoengineer as Translator

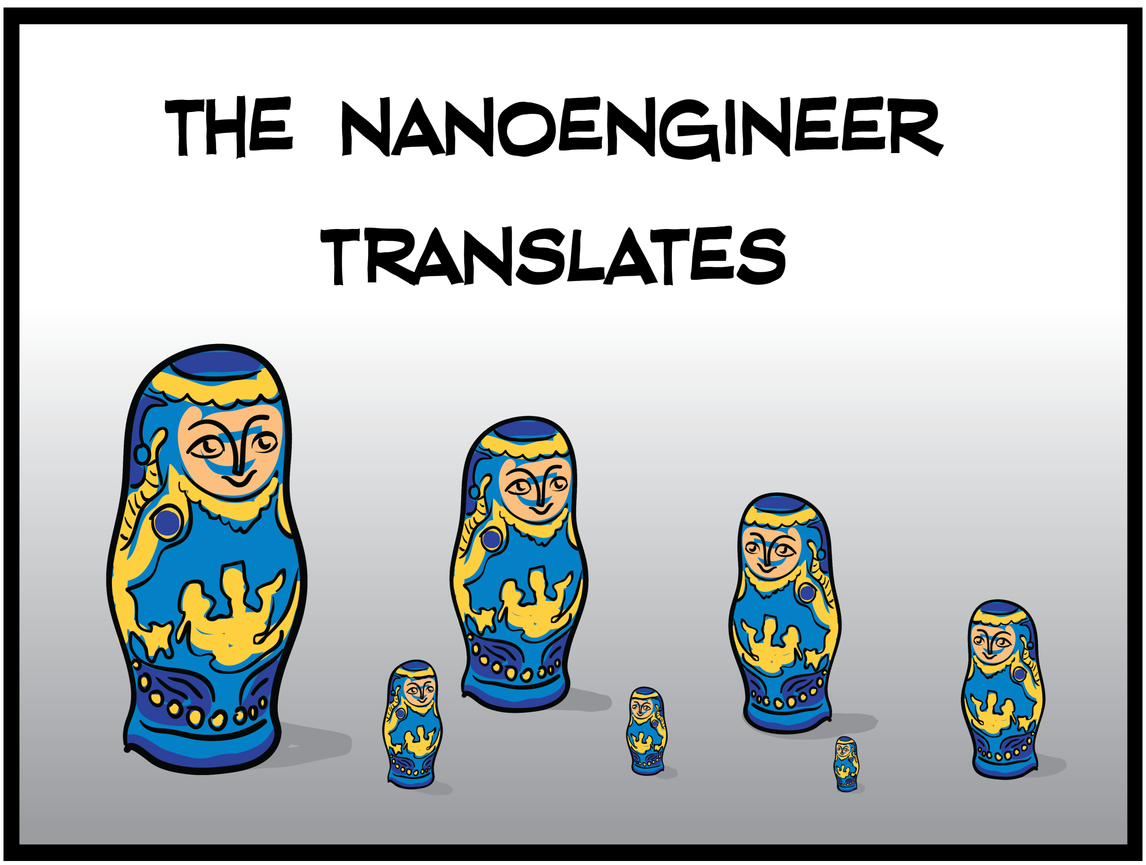

Illustration 131 The nanoengineer as a translational figure.

According to the *Engineer of 2020* report that served as a guide for creating the undergraduate curriculum, the engineer is key to the processes of commodification:

> As research activities mature, efforts to transition the new knowledge from laboratory products into marketable products will increase and so too will the involvement of engineers. Products will increasingly support commoditized biosystems, ranging from artificial organs and implantable devices to other 'sustainable systems.'[58]

Here, the engineer is central to the process of transitioning laboratory products into marketable products. While the market is the nexus of exchange between science and society, the nanoengineer must conduct multiple kinds of translations to facilitate this dynamic. Recall that translational research produces and brings to the market place new products and processes, the definition of innovation. One way to examine how the framework of translational research informs the research process is to look at how nanoengineers conceptualize and articulate what makes their work innovative, or novel *and* marketable. Identifying what makes something innovative is a precursor, and sometimes blends into, what I've been calling promissory visioning, following Kaushik Sunder Rajan. Sunder Rajan locates promissory discourses of the future at the intersection of science and capitalism, where attracting capital investment for research requires the articulation of a vision for the value of research outputs in the future.[59] Often the articulation of what makes a research project innovative and beneficial is bound up

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58. National Academy of Engineering, *The Engineer of 2020: Visions of Engineering in the New Century*, National Academies Press, 2004, 11.

59. Kaushik Sunder Rajan, *Biocapital : The Constitution of Postgenomic Life*, Durham: Duke University Press, 2006, 110-116. Sunder Rajan articulates this in terms of hype, which is less about what is real or unreal than about what is credible or incredible. I use the term less to claim any particular vision as hype or not, but to connect the promissory aspect of the nano dream with the political economic necessities of attracting investment.

with the political economic needs of attracting capital investment in the research project. For my analysis, I looked at twenty-one publicly available grant proposals by eight nanoengineering faculty, and I interviewed eight faculty. The eight faculty interviewed overlap with those whose funding proposals I am analyzing, but there are also funding proposals authored by faculty whom I have not interviewed. I supplement this with analysis of faculty publications and laboratory websites, which detail the research groups and the research projects occurring in each lab.

Though much of the translational work nanoengineers do is not unique to nanoengineering, their particular relationship to translating across scale and discipline makes all of these translations part of constituting a good fit with the translational paradigm. That is, nanoscale materiality has particular properties and behaviors that, according to nanoengineers, demand a unique set of skills that involve translating and crossing boundaries, such as interpreting the invisibility of the nanoscale through visible cues and indices; bridging quantum mechanics with classical mechanics; understanding multiple disciplinary fields as they converge at the nanoscale; and learning to control nanoscale matter through indirect means, like creating the particular conditions that

Illustration 132 Distinguishing between 80nm and 100nm by visually assessing the color of nanoparticles in solution.

enable and constrain nanoparticles to assemble in specified ways.

Other forms of translational work that are not necessarily unique to nanoengineering nevertheless come to fit within this translational identity.[60] Nanoengineers translate their work into a progressive succession of problems and solutions; they translate between nanoscale mechanisms in nature and manmade nanotechnologies, across scalar regimes, between simulations and experimental observations, and between disciplinary knowledges; and they translate research outputs into products and processes. Translation here is not merely linguistic, or a set of practices aimed at preserving meaning; translation is productive of meaning and it is also material. We might understand the fluency with which nanoengineers facilitate knowledge production across the translational continuum, and across scale, disciplinary boundaries, and registers in terms of *translatus*—the movement, or carrying over, from one medium to another. This is a transformative process. The nanoengineer must be the ultimate translator to produce novelty and to channel it into innovation, which is to say, to commodify knowledge as part of translational research. Translation is an interpretive act, producing knowledge and technology *as* innovation for the benefit of society, uniting the utilitarian goals of an efficient, rational, market-driven research process with the utopian goals of universal benefit. Here I will elaborate on several ways that the nanoengineer's active role as a translator articulates the broader imperatives of translational research.

60. Even though the term "translational research" is used frequently in the department, not all nanoengineers would use the term "translation" as a label for themselves, even if they describe what they do in terms of these kinds of translations. My use of the phrase "translational figure" emerges through my analysis as one that fits nanoengineers' descriptions of what they do, and therefore makes the paradigm of translational research a good fit. One nanoengineer I asked about this term in an informal conversation indicated that he had been thinking of nanoengineers as "brokers" for similar reasons.

Problem and Solution

One translation nanoengineers must perform in order to articulate the utility and novelty of their work is that between problem and solution. I call this a translation because what constitutes a problem or a solution, and the relationship between the two, is the effect of interpretive acts that frame the research process as one that is efficient, rational, and progressive. The problem that a research project is geared toward solving is articulated as the starting point of innovation, although this must be understood as a figurative starting point that may or may not occur temporally at the beginning of a research project. Institutional and funding requirements, and the cultural and translational imperative to solve problems all contribute to the necessity of articulating the problem as the starting point. In practice, however, such a starting point must be understood in the context of a research trajectory, where new problems emerge from the research process. And sometimes research discoveries are articulated as solutions to problems that have been identified only after the fact. For example, one faculty PI indicated in an interview that only when her team did a literature review in preparation for publication did they realize that their research had implications for a whole range of applications that they had never before considered.[61] This allowed them to frame their findings as solutions to multiple problems that were nevertheless irrelevant to them at the beginning of their research project and which certainly did not drive the research process.

Regardless of which comes first, the nanoengineer must translate her work into problem-solution pairs, grounding knowledge production in utilitarian terms. The

61. Interview with NanoEngineering professor, February 4, 2011, transcribed by author.

production of something new is done *in order to* address a problem. In the context of articulating problem-solution pairs, novelty materializes as a solution to a problem, even if it simultaneously produces the problem that the solution is addressing. I will briefly show how this occurs in relation to the four most common articulations of the problem I identified in this dataset: the problem can be framed as a technical challenge that impedes an application goal, a shortcoming identified in the "state of the art" of a particular domain, a gap in making something commercially viable, or a gap in fundamental knowledge.

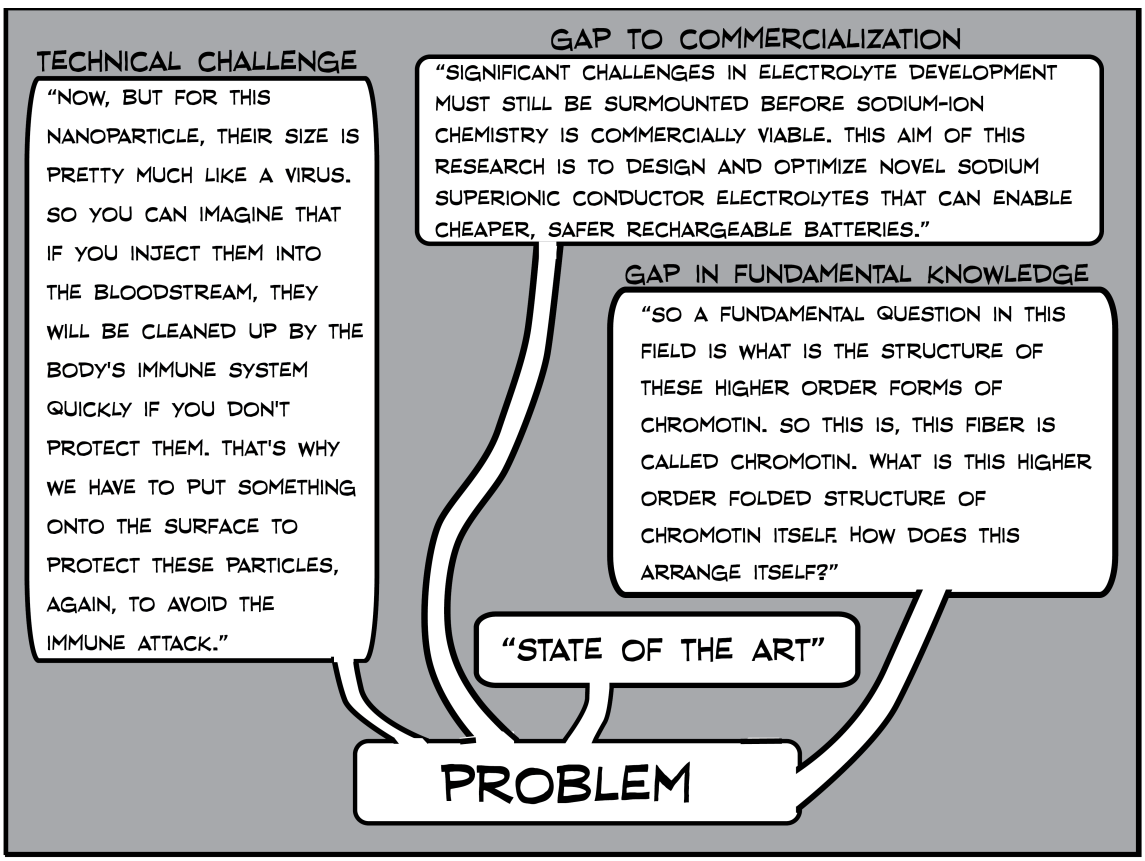

Illustration 133 Articulating the problem.

The first, a technical challenge in realizing an application, most often emerges in the context of a research trajectory. The nanoengineer engages in promissory visioning to describe an application that will solve a universal problem and provide a solution for mankind, and in the pursuit of solving this grand challenge, the immediate problem—the technical challenge—emerges in a processual way in the research process. Articulating these smaller problems and solutions within the larger trajectory of this grand challenge effects the linear temporal procession of translation and unites the utopian horizon of universal benefit with the utilitarian means of achieving it. The ultimate solution to the grand challenge is expected to materialize in the future, and through each problem-solution pair, time and progress are enacted. For instance, nanobot targeted drug delivery is an application—the grand solution—that can solve the ultimate problem of cancer, or more specifically, the problems of current cancer therapies that are devastating to the human body and not always effective. But the immediate problem—the technical challenge on the way to that broader goal—becomes a solvable stepping stone, enacting the progressive development of a research trajectory. A nanoengineer who is working on developing targeted drug delivery for nanomedicine applications discusses one of the immediate technical challenges that must be solved. This is the problem of the immune system attacking the nano carrier vehicles (nanoparticles) that would deliver medicine directly to tumor cells:

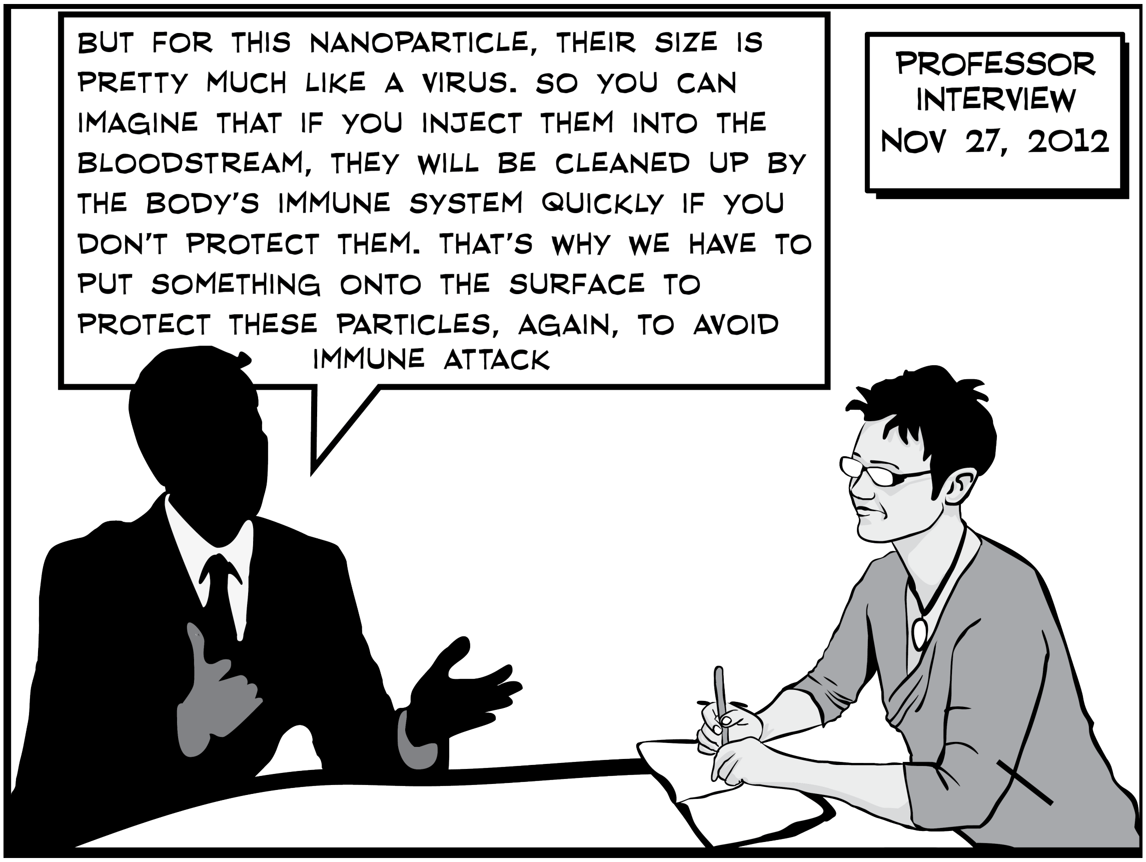

Illustration 134 Interview with NanoEngineering professor. "But for this nanoparticle, their size is pretty much like a virus. So you can imagine that if you inject them into the bloodstream, they will be cleaned up by the body's immune system quickly if you don't protect them. That's why we have to put something onto the surface to protect these particles, again, to avoid immune attack."[62]

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This problem of immune system attack has to be solved to have a successful drug delivery platform. The research is done in order to solve this problem, which brings the researcher closer to the future moment of producing the ultimate solution, a new cancer therapy. In the process, the researcher develops an innovative approach to protecting nanobots from the immune system. By translating research into problem-solution pairs, the nanoengineer unites the utility and utopian horizon of his research, effecting an

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62. Interview with NanoEngineering professor, November 27, 2012, transcribed by author.

efficient, rationalized, and progressive movement toward marketization that simultaneously heralds the broader goal of innovating for the benefit of society.

The problem can also be articulated in terms of identifying the shortcoming in the current "state of the art." This particular kind of framing for problems and solutions highlights the ways that translation, as a set of best practices, governs according to assumptions about novelty and progress. For example, a nanoengineer who works on batteries says: "So we start with the state of art, and then we realized the problems of the state of art."[63] Identifying problems in the state-of-the-art can be considered a best practice of translational research. By situating one's research with respect to the state-of-the-art, whatever is understood as the latest-and-greatest in the specified domain is implicitly problematized. The state of the art becomes insufficient compared to the utopian horizon of what it could be. At the same time, the effort to produce a solution, insofar as this research process is now articulated as a problem-solution pair, is organized in terms of the translational imperative of utility. The solution, which will represent novelty and progress, instantiates a new state-of-the-art in the domain. Certainly a common way to frame the problem outside of nanoengineering as well, as are all of these ways of articulating the problem, pushing the state-of-the-art effects a naturalized movement toward the future in which the new *is* the improved, so that such research is definitionally useful. Each new and improved instance of the state-of-the-art is not in itself the utopian horizon, but it reasserts the inevitability of progress toward utopia.

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63. Interview with NanoEngineering professor, February 5, 2013, transcribed by author.

The problem is also often articulated as a hurdle on the way to commercialization, a framing that explicitly emphasizes the principle of utility in translational research. For example, in a grant proposal, this researcher identifies something that may already be do-able but not in a commercially viable way:

> Sodium-ion rechargeable batteries are a potentially cheaper and more abundant alternative to lithium-ion batteries. However, significant challenges in electrolyte development must still be surmounted before sodium-ion chemistry is commercially viable. This aim of this research is to design and optimize novel sodium superionic conductor electrolytes that can enable cheaper, safer rechargeable batteries.[64]

Although this is probably also true in engineering more generally, within the imperative of translational research, problems of commercialization are as valid as any other form of technical challenge. Recall that to constitute innovation, not to mention intellectual capital, research products from this department must enter the market place. Moreover, only by solving the problems of commercialization can products avoid the destiny of "end[ing] up on the shelf," as the dean put it in his welcome speech. Utility is not secured until the final stage of the translational research process, when products reach the market.

Finally, a problem can be framed as a gap in fundamental knowledge, illustrating that translational research does not simply replace basic research with applied, but rather incorporates basic research into the continuum of translation/commercialization. The justification for closing a gap in fundamental knowledge is framed in instrumental terms. For example, in the following grant proposal, the "thorough understanding" being pursued is nevertheless situated within the larger objective of fabricating devices:

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64. Principal Investigator, National Science Foundation funding application (NSF: CMMI), 2014.

> New functionality in nanomagnetic devices requires control of magnetic order at the nanometer spatial scale and sub-nanosecond temporal scale. Many spin-based devices are still in their infancy and a thorough understanding of the underlying materials and electronic properties and their effect on device performance will be essential for future applications.[65]

As I previously indicated, faculty researchers may be motivated to pursue fundamental questions by their genuine curiosity, but curiosity, pleasure, and the non-utilitarian concerns sometimes associated with basic research are insufficient justifications in the context of a funding application. Utilitarian and non-utilitarian justifications can coexist for faculty, but what they must articulate within the context of the political economy of nanoengineering and research more generally, and within the institutional imperative to articulate nanoengineering as translational research, is how their research on the basic properties and behaviors of matter on the nanoscale is relevant for future applications. As translational research, a particular project does not have to be flagged as "basic" or "applied," and the utopian horizon might be quite broad and unspecified, but its utility, or at least its promise of utility, must be articulated.

My analysis here is not to suggest that there is something artificial in the ways that these problems are identified and paired with solutions, as if there were another more natural way to articulate the goals, justifications, and outcomes of science and engineering research. Rather, I identified the ways in which research along the translational continuum, from closer to further from marketization, is oriented toward the market place, how it unites utility with utopia, and effects a linear narrative of progress

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65. Principal Investigator, National Science Foundation funding application (NSF:DMR), 2013.

toward innovation for the benefit of society. In fact, what counts as a good problem within this framework is one that can be articulated in these terms. The solution to such a problem is constituted as benefit: it is valued by the market, it is useful, and by solving a problem it effects progress and heralds the utopian horizon.

Man and Nature

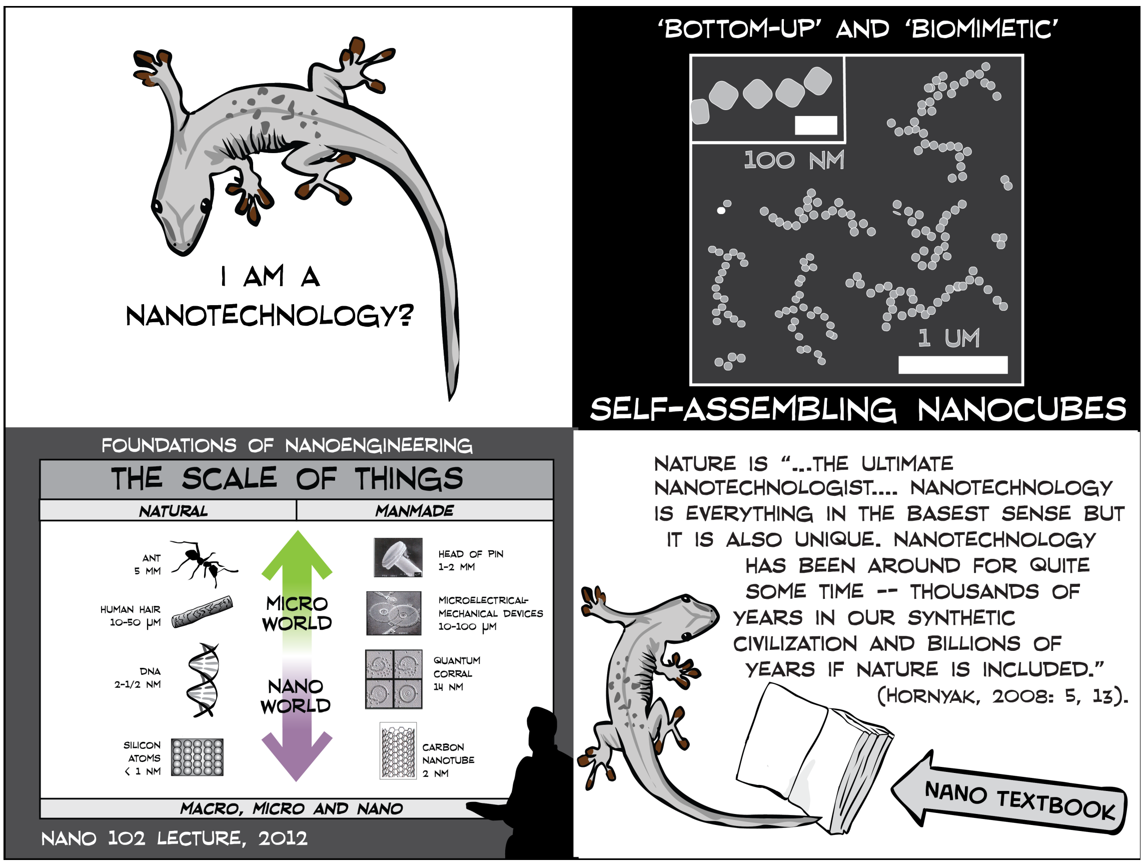

Illustration 135 Translating between nature and man.

Like many other domains, nanoengineering looks to nature as a source of inspiration. The nanoengineer learns to translate nature's nanoscale properties and behaviors into nanotechnological innovation. In doing so, nature is often understood in utilitarian and mechanistic terms, producing maximally efficient organisms and structures, as I discussed in Chapter 4. By mimicking nature, nanotechnological innovation is again located at the intersection of utility and utopia—designed to be efficient and natural, and to maximize usefulness and benefit while minimizing waste and risk. In Chapter 2, I suggested that articulating nanoengineering in terms of biomimicry implicitly associates the field with a set of signifiers such as natural, safe, and good. These characteristics help to position nanoengineering innovation in terms of its utopian horizon. Even though not every single research project has an explicit natural referent, nanoengineering is still framed as intrinsically biomimetic because the organic world—with its geckoes, butterfly wings, and plankton, to name a few instances—is already nanotechnological. Yet, as I will show in the following example, this kind of translation—from the natural world to the manmade—doesn't necessarily stop at mimicking; similar to the ways that translation replaces the categories of basic and applied, it locates natural and manmade within its continuum toward the marketplace and undoes any categorical distinction between the two.

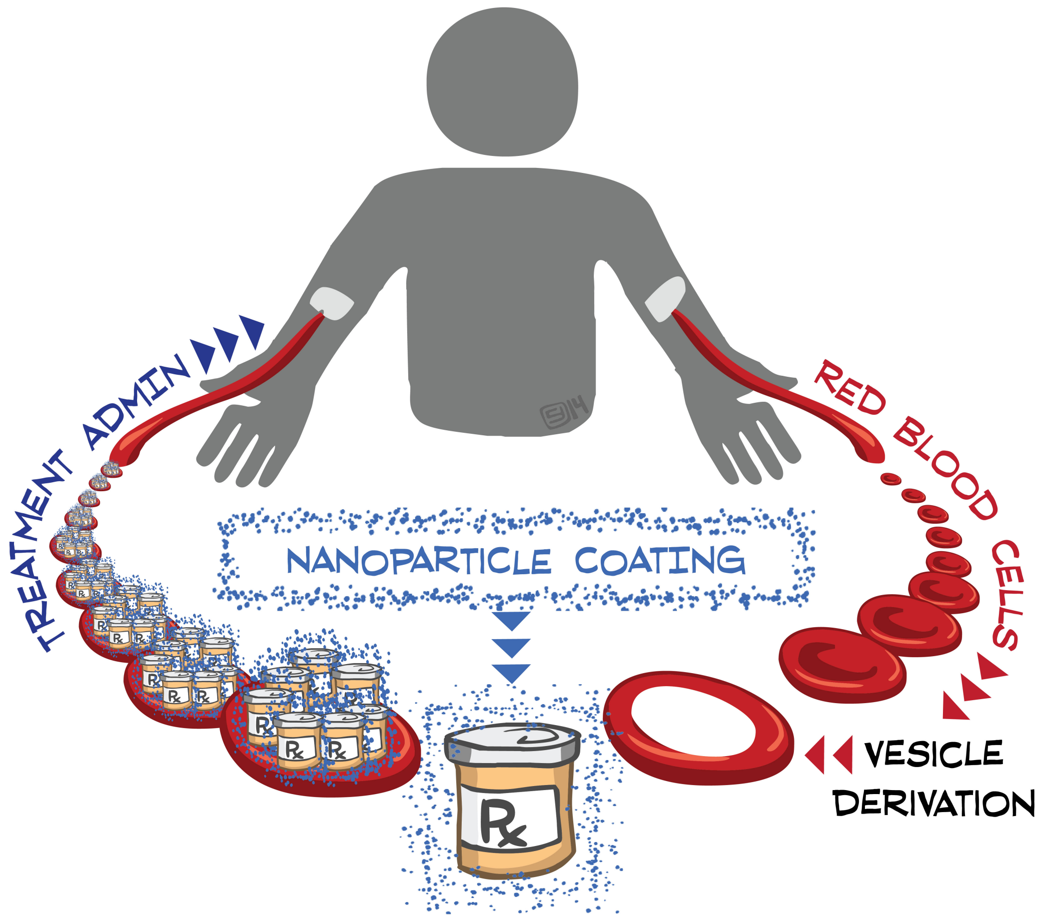

Illustration 136 Nanomedical research using red blood cells for targeted drug delivery.

There is a nanoengineering professor in the department who is working on drug delivery using red blood cells (RBCs). Here, the narrative of biomimicry begins with inspiration, but quickly exceeds both inspiration and mimicry. First, in tackling the problem of how to safely protect nanoparticles (NPs) in the human bloodstream from attack by the immune system, the PI described having tried for a couple of years to develop synthetic coatings for NPs. He indicated that this was the general direction of most research aiming to safeguard NPs in the bloodstream, with different labs primarily focusing on different proteins to adhere to the synthetic coatings. However, this approach was problematic because it was very difficult to manufacture such a coating that would protect the NP from the immune system and not break down in the body. Then he described a new inspiration that came from nature:

> Instead of hiding something in the system, we camouflage our particle, like it belong to the body (*sic*). So this overall idea is inspired by red blood cells. In the body we have lots of these red blood cells. They can circulate very long. One millimeter, 1 cc blood, has 10 billion red blood cells inside. And all these cells circulate in the body so long. The question is why is that? Why the body's immune cells do not attack your own red blood cells? There must be something there.[66]

Once he identified the RBC as a source of inspiration and an object to investigate more closely for ideas about how to protect the nanoparticle, he might have innovated a new synthetic coating that modeled, or mimicked, the RBC. But instead he describes a different research trajectory:

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66. Interview with NanoEngineering Professor, November 27, 2012, transcribed by author.

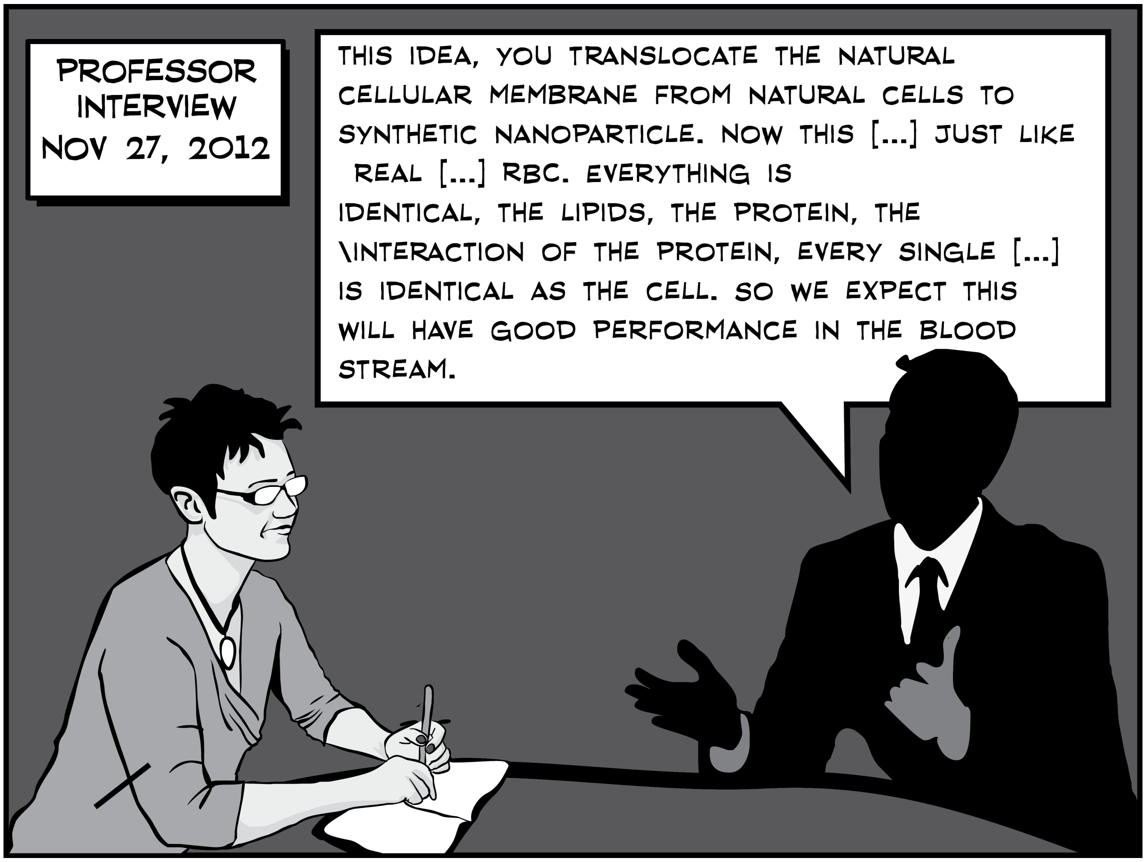

Illustration 137 Professor interview. "This idea, you translocate the natural cellular membrane from natural cells to synthetic nanoparticle (sic). Now this [...] just like real [...] RBC. Everything is identical, the lipids, the protein, the interaction of the protein, every single [...] is identical as the cell. So we expect this will have good performance in the blood stream."[67]

That is, he has innovated a process that takes the RBCs, removes the insides so that he has only the RBC membrane, and then inserts the NP into this RBC membrane. Rather than mimicking the RBC membrane, he is actually using it, translocating the NP inside it. No longer just mimicry, what he has developed is not merely *like* the RBC, but *is* simultaneously the RBC and the NP, a new natural technical object. By emphasizing that through translocation of the membrane (another kind of carrying over) everything is

67. Ibid. The square brackets and ellipses indicate a word I was unable to understand from the audio recording, and therefore could not transcribe.

identical, he is saying there is no distinction to be made now—at least from the outside—between the RBC (natural object) and the NP (manmade object). The material and functionality of nature are carried over into the manmade world:

> The research objective of this award is to study an innovative biomimetic nanoparticle platform that uses natural red blood cell (RBC) membranes, rather than conventional synthetic stealth biomaterials, to cloak synthetic nanoparticles for drug delivery. The approach taken will be to utilize a novel and revolutionary top-down strategy to functionalize nanoparticles by transferring the entire cellular 'utility coat' of an RBC onto the surface of drug nanocarriers. A nanoparticle thus modified is expected to exhibit similar physiologic behavior as its source cells.[68]

Here the translational work between nature and man is central to what makes it "innovative" and "novel and revolutionary." On the one hand, the language of this funding proposal reifies the division between natural and manmade, juxtaposing the "natural red blood cell membranes" with the "synthetic nanoparticles." On the other, what is considered natural is already understood in terms that sound manmade, such as "utility cloak" to describe the RBC membrane. Nature's nano is utilitarian, and old idea. But in this formulation, nature is folded into the translational continuum: from a mechanized nature on one end to the naturalized market on the other, translational research commodifies natural-technical knowledges and materials. And the nanoengineer's ability to translate nature into nano is key to making this happen.

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68. Principal Investigator, National Science Foundation funding application (NSF:DMR), 2012.

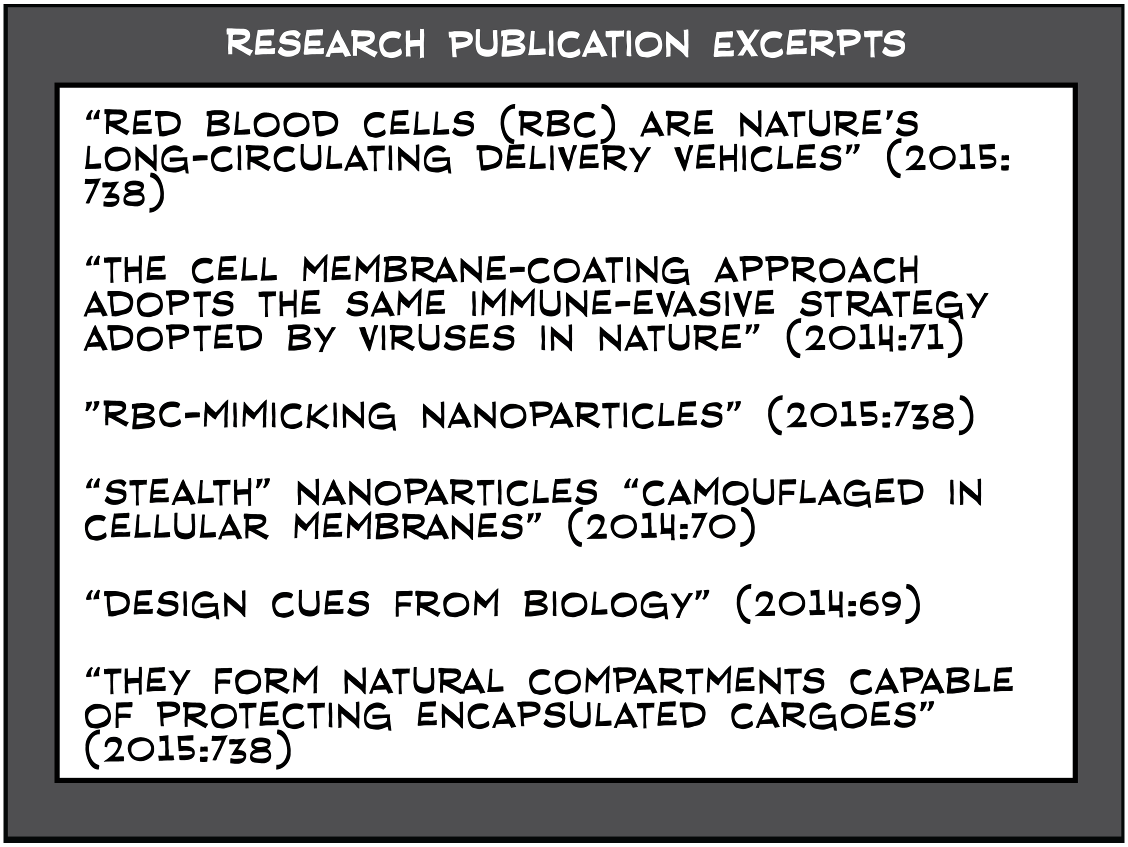

Illustration 138 Research publication excerpts. "Red blood cells (RBC) are nature's long-circulating delivery vehicles.[69] "RBC-mimicking nanoparticles."[70] "They form natural compartments capable of protecting encapsulated cargoes."[71] "The cell membrane-coating approach adopts the same immune-evasive strategy adopted by viruses in nature."[72] "Stealth" nanoparticles "camouflaged in cellular membranes."[73]

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69. Weiwei Gao and Liangfang Zhang, "Engineering Red-Blood-Cell-Membrane-Coated Nanoparticles for Broad Biomedical Applications," *AlChE Journal* 61, no. 3 (2015): 738.

70. Ibid.

71. Ibid.

72. Che-Ming J. Hu, Ronnie H. Fang, Brian T. Luk, and Liangfang Zhang, "Polymeric Nanotherapeutics: Clinical Development and Advances in Stealth Functionalization Strategies." *Nanoscale* 6 (2014): 71.

73. Ibid., 70.

Simulation and Experiment

Another interesting axis of translation occurs between simulation and experiment. The tight cycles between simulation/computation and laboratory experiment are described by many nanoengineers as integral to what makes nanoengineering a novel practice producing novel things. Relying heavily on simulation and computational methods to narrow the range of possible parameters for laboratory experiment reduces reliance on trial and error, making the machinery of innovation rapid and efficient. Using simulation and computational methods in this way might be considered a best practice of translational research. The simulation and experimental practice is often done in parallel, as explained in this interview:

> PI
> And so, what he found was, okay, there's a very specific transition between a short and a long polymer corresponding to four monomer units of polymer, and we actually demonstrated based on his calculations that with four monomer units of polymer, we can get these particles to assemble face-to-face.
>
> Emily York
> So he did the simulations first?
>
> PI
> Um, we kind of did them in parallel.
>
> Emily York
> Okay.
>
> PI
> So we first found that, okay, we could assemble these particles in a polymer, and then we were noticing all these weird junctions, basically we're like, oh, okay, these particles are actually assembling with some kind of specific orientation. And then we went to [him] with this problem, and he kind of modeled it, and he said, Okay, well, there should be this specific transition between what you're seeing and what you expect to see, which is a face-to-face configuration. And so then we showed that that transition actually exists.

> Emily York
> Uh huh. Cool. So there's this kind of back-and-forth between the experiment and the theory and the simulation, very cool.
>
> PI
> Yeah, yeah. Yeah, it actually was cool, because normally it doesn't happen like that. [laughter] Normally you play around in the lab until you get something, and those kinds of experiments take a very long time. Whereas if you can actually do some theoretical calculations or simulations that can tell you what you should expect, you can engineer your materials to get that result. And in that case, the science experiments go a lot faster.[74]

In this interview, the professor describes a process in which simulations generate particular expectations that are translated into an experimental apparatus in the lab. The experimental results are then translated into updated simulations, and this back-and-forth between simulation and experiment, each informing the other, occurs until there is agreement between the results of each. The PI describes this as speeding up the entire process, speaking to the imperative of rapid and efficient innovation. In a funding application, a description of the role of simulation demonstrates its centrality to the innovation process:

> Molecular simulations will be used to deduce the global phase diagram of the multicomponent nanocrystal-polymer mixtures and to predict the mechanisms and kinetics of large-scale nanocrystal assembly. Guided by simulations, nanocrystals will be chemically modified by polymer grafts with tailored chain lengths, grafting density, and charge.[75]

Here, simulations are "used to deduce," "to predict," and "to guide." Importantly, this movement back and forth between simulation and experiment relies on theoretical work

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74. Interview with NanoEngineering professor, November 14, 2012, transcribed by author.

75. Principal Investigator, National Science Foundation funding application (NSF:CMMI), 2012.

and fundamental knowledge production as well as a clear idea about the application goals and ends of the research process, something usually associated with applied research. Another nanoengineer describes how computational methods are integral to the design of new materials, and here it is particularly clear that the PI has a definite product in mind—a new material with specific properties—and that computational methods enable an efficient way to identify the optimal design for achieving these properties:

> Yes, well we actually designed the new compositions of the materials through a combination of computational method. So it's experiment, so we utilize, it's called First Principles Calculations to help us in the materials design stage. So we actually design the compositions, it's like reverse materials design. You know the properties you want to achieve, and then you design the materials. And in this case, the students were actually able to synthesize the design of the materials, and then we prove that these designed materials does actually perform much better than the state of art.[76]

Through translations between simulation and experimental apparatus, the nanoengineer is able to more quickly and efficiently produce useful objects that can then be brought to the market place.

The "Implication" is the "Application"

The universal goal of benefitting society neither originates with nor is limited to nanoengineering.[77] And it is sustained, at least in part, through institutional structures and funding mechanisms, such as the NSF, which explicitly solicit grant applicants to frame research and development in these terms.

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76. Interview with NanoEngineering professor, February 5, 2013, transcribed by author.

77. Robert Nisbet, *History of the Idea of Progress*, New Brunswick, N.J.: Transaction Publishers, 1994. According to Nisbet, the universal category of society as the referent for progress emerges with Christianity.

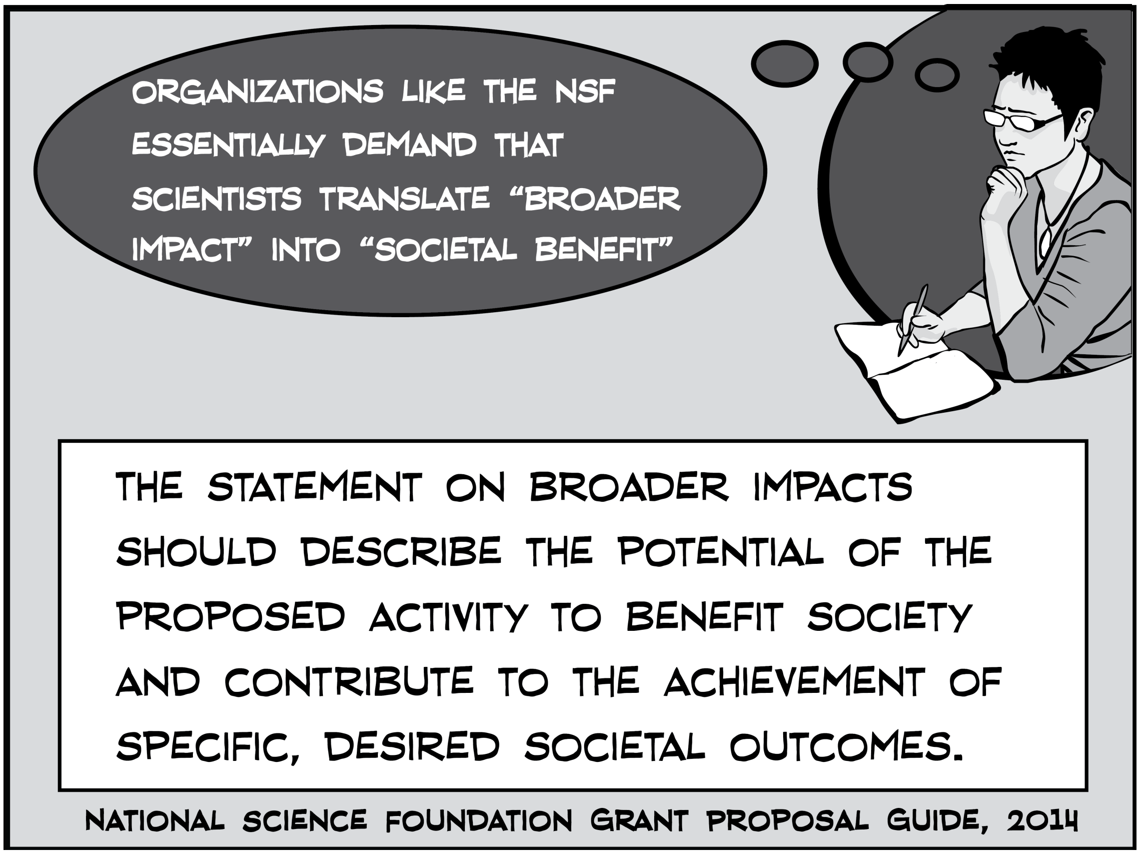

Illustration 139 Broader impacts as societal benefit. "The statement on broader impacts should describe the potential of the proposed activity to benefit society and contribute to the achievement of specific, desired societal outcomes."[78]

What might constitute such benefit is further elaborated as follows:

> Broader impacts may be accomplished through the research itself, through the activities that are directly related to specific research projects, or through activities that are supported by, but are complementary to the project. NSF values the advancement of scientific knowledge and activities that contribute to the achievement of societally relevant outcomes. Such outcomes include, but are not limited to: full participation of women, persons with disabilities, and underrepresented minorities in science, technology, engineering, and mathematics (STEM); improved STEM education and educator development at any level; increased public scientific literacy and public engagement with science and technology; improved well-being of individuals in society; development of a diverse,

78. National Science Foundation Grant Proposal Guide, II-2, December 26, 2014, http://www.nsf.gov/pubs/policydocs/pappguide/nsf15001/gpg_2.jsp, accessed February 1, 2016.

> globally competitive STEM workforce; increased partnerships between academia, industry, and others; improved national security; increased economic competitiveness of the United States; and enhanced infrastructure for research and education.[79]

That is, the political economy of nanoengineering, whether examined from the context of market dynamics or from the perspective of national funding regimes (also part of market dynamics) requires a researcher to highlight societal benefit. In doing so, the "impact" of nanoengineering is understood as the application that will confer this benefit, not as the potential complexity emerging from a research trajectory which may or may not confer benefit.[80] Nanoengineering proposals which articulate broader impact in terms of societal benefit, then, are being asked to do this. Nanoengineers must translate knowledge production into a promissory vision of benefit, connecting the utility of their research with its utopian horizon. The NSF proposal guidelines articulate a number of different kinds of benefit that would count within a "broader impacts" assessment, and not surprisingly, benefit is variously articulated in the funding proposals I analyzed. In the following NSF Broader Impact statements, for example, benefit is at least in part economic:

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79. Ibid. While the NSF proposal guide mentions "broader impact" 26 times, it mentions risk and implications each just 3 times, and in each case only one of these mentions is in the context of the research itself. Risk is mentioned in the context of protecting human subjects from research risks, and implications are mentioned in a statement regarding selection criteria for reviewers, indicating that reviewers with broad expertise are required in the case of "significant national or international implications" (III-3)]

80. STS research engaged in the "implications" of science and technology tend to focus on potential adverse effects or impacts that may be otherwise unanticipated. Robin Williams writes that "the ELSI Research Programme, founded in 1988, received 3-5 percent of the total funding for the US Human Genome Project….James Watson promoted the ELSI programme with the ambitious objective 'to address, anticipate, and develop suggestions for dealing with such problems in order to forestall adverse effects'" (Robin Williams, "Compressed Foresight and Narrative Bias: Pitfalls in Assessing High Technology Futures," In *The Yearbook of nanotechnology in society, Volume 1, Presenting futures,* edited by Erik Fisher, Cynthia Selin, Jameson M. Wetmore and David H. Guston [Dordrecht]: Springer Science, 2008, 284).

> Develop new educational components that will "enable impact on a national level" and that will "…seek to develop human resources in advanced technology, which is vital to **economic growth** in California and the U.S. as a whole."[81]
>
> Help **remediate the environment and create jobs** in an economy that includes renewable energy.[82]

The first articulates economic benefit that emerges through the development of education and human resources, framed in Chapter 5 in terms of human capital. The second connects the possibility of environmental benefit with job growth. In the following broader impact statement, benefit is conferred through new processes that support nationalism:

> …[It will] add to the scientific knowledge base in laser material processing, a strategic area in advanced manufacturing that **helps maintain the US leading position in the world**….and….will add to the scientific knowledge base in laser material processing, a strategic area in advanced manufacturing that helps maintain the US leading position in the world. The proposed research will not only stimulate scientific discovery, but also provide opportunities for student training and **technology transfer**.[83]

In addition to contributing to human and intellectual capital—represented by "knowledge base" and "student training," and "technology transfer" respectively—these outcomes are framed in terms of benefit to the nation state. In the following excerpts, benefit is produced through medicine, or life extension:

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81. Principal Investigator, National Science Foundation funding proposal (NSF:EEC), 2014, emphasis added.

82. Principal Investigator, National Science Foundation (NSF:EEC), 2013, emphasis added.

83. Principal Investigator, National Science Foundation (NSF:CMMI), 2011, emphasis added.

> [It will] push forward the frontier of current nanomedicine research by providing therapeutically relevant quantities of drug-loaded nanoparticles for possible **clinical use**.[84]
>
> [It will] "open a new area of research ..." and "…provide a brand new approach to treat MRSA and S. aureus related infections, thereby benefiting the **entire community of patients with MRSA** infections consisting of over 126,000 patients per year in US."[85]
>
> Such a combination of natural cellular components with synthetic biomaterials presents an innovative approach to develop novel and powerful drug delivery nanocarriers and will have profound impacts on the fields of biomaterials research and nanotechnology drug delivery.[86]

These applications highlight clinical use for medicine and drug delivery that directly improves the lives of patients as well as further scientific research in the field. These research projects are most closely related to the traditional use of the term "translational research." Finally, in the following excerpt benefit is articulated in terms that are universal: [It] "...directly aids scientific progress, [and] benefits healthcare and society at large."[87] In each of these cases, knowledge production is aimed at producing new products or processes that can be brought to market, where value that in economic terms is based on private, rival, excludable goods, is here translated into public, universal (or at least national) benefit. If nanoengineers become experts at translating their research into innovation for the benefit of society, it is expertise that is demanded by the political economy of nanoengineering.

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84. Principal Investigator, National Science Foundation funding application (NSF:CMMI), 2010, emphasis added.

85. Principal Investigator, National Institute of Allergy and Infectious Diseases, 2010, emphasis added.

86. Principal Investigator, National Science Foundation funding application (NSF:DMR), 2012.

87. Principal Investigator, National Science Foundation funding application (NSF:CMMI), 2013.

As a new discipline arising coterminously with the ascent of translational research and the political rationality that underlies it, nanoengineering is well-suited to adhere to this mode of governance. Translation is an embodied, interpretive act, and the nanoengineer cannot do translational research without herself translating across scales, disciplines, materials, modalities, registers, institutions and collaborative partnerships. Her translations are multiple, simultaneously adhering to the imperatives of the translational research framework—orientating her work toward the market, conducting knowledge production as an efficient, rational, and utilitarian process—while also securing her some flexibility in how she does this. The moniker "translational research" circulates usually without asking who or what does translation, as if there could be translation without translators. This is in line with ideals of governance that would propagate best practices without agents. But in fact translation does require translators, and the nanoengineer as the key translator in the translational apparatus of nanoengineering innovation has some agency in reconciling the imperatives of her research with those of her field, department, and university.

Conclusion

The NanoEngineering department describes nanoengineering as translational research, and in this chapter, I've tried to understand why this term—which usually describes biomedical and clinical research—has been taken up in this site even though only a portion of nanoengineering research is medically relevant. In doing so, I've also considered how nanoengineering as translational research maps to the department's claim that it is an innovation ecosystem and that it is innovating for the benefit of society. To the extent that translational research signals commercialization and an orientation toward the market place, it maps neatly to the engineering school's vision of producing intellectual capital and to the economic definition of innovation, which is to bring new processes and products to the market place. To the extent that translational research also demands an efficient, rational research process that effectively moves research out of the lab and into society to be used, it fits well with the utilitarian demands of the department that promises its outputs will be used by people. To the extent that upon reaching society, research outputs are understood in terms of progress and universal benefit, it becomes a framework for knowledge production and commodification that unites utility and utopia. Figuring all research in terms of economic conduct, it positions the market as the necessary turnstile through which social problems are mapped to engineering solutions, and engineering solutions to societal benefit. But this turnstile cannot produce the meaning of what passes through on its own; the market does not identify social problems or engineering solutions. Translational research needs a translator, and the nanoengineer is an ideal translator. Already located at the intersection of multiple scales and disciplines and at the intersection of university, industry, and state, the nanoengineer is constituted as a translational figure whose engineering ethos, which champions efficiency and utility, and whose nano dreams of societal benefit find a place within the framework of translational research. Moreover, through her facility and fluency in performing multiple translations, in framing and reframing her work to meet the demands of the political economy of her research and the institutional requirements where she conducts her work, the nanoengineer also maintains some agency in determining how her research projects fit within the translational continuum. Research that is more fundamental and further from marketization can be pursued, so long as she can obtain funding, articulate its relevance to future applications, and pursue other projects that are closer to marketization. Through translational research, the nanoengineer in charge of her laboratory in a research university can pursue her nano dreams, so long as they are pursued rationally and efficiently, and offer some possibility of becoming capital.

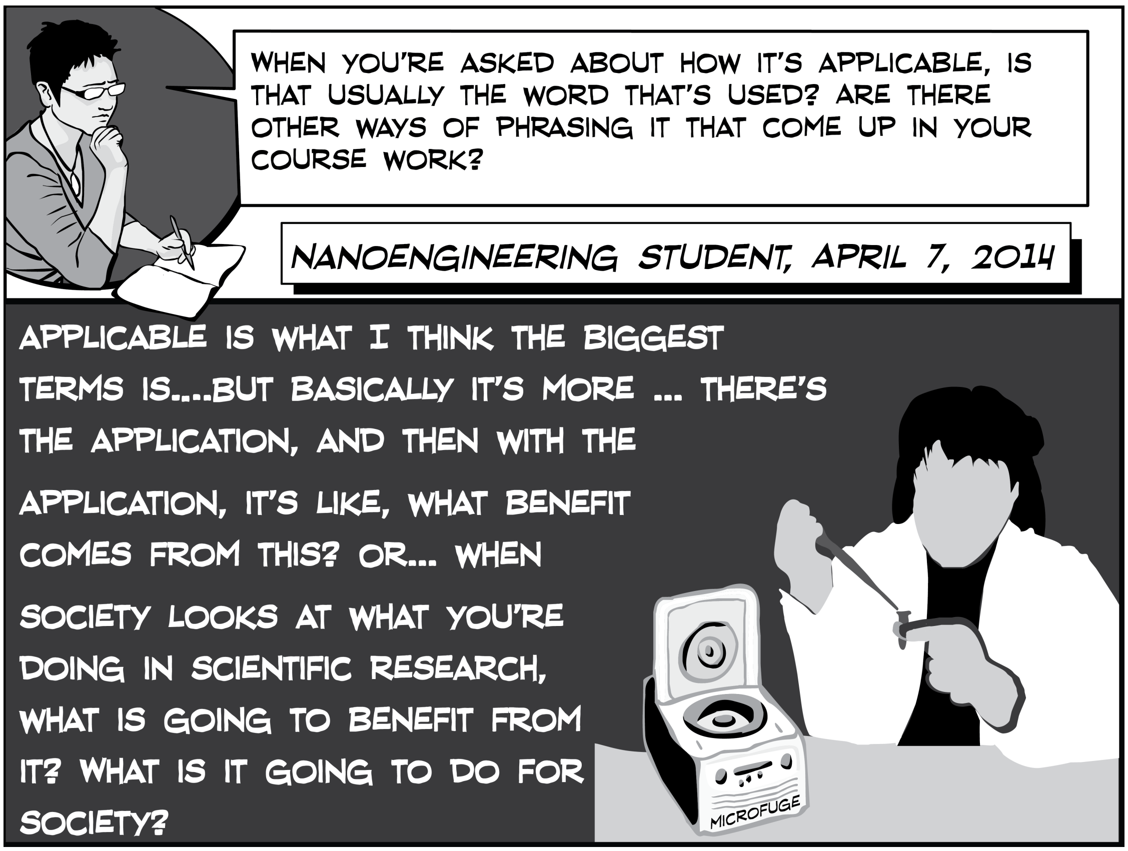

Illustration 140 Applicability associated with benefit.[88]

88. Interview with NanoEngineering student, April 7, 2014, transcribed by author.

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Conclusion: A Future History of Nanoengineering

The simple and basic question I began with was, What is nanoengineering and who are its practitioners? Yet the answers to this question point beyond the emergence and disciplinary formation of a scientific field to raise many more questions: What counts as benefit and progress? Whose futures come to matter through technoscientific worlding? What kind of ethics or responsibility is possible in an innovation economy? And what might constitute thought under a regime of capital accumulation?

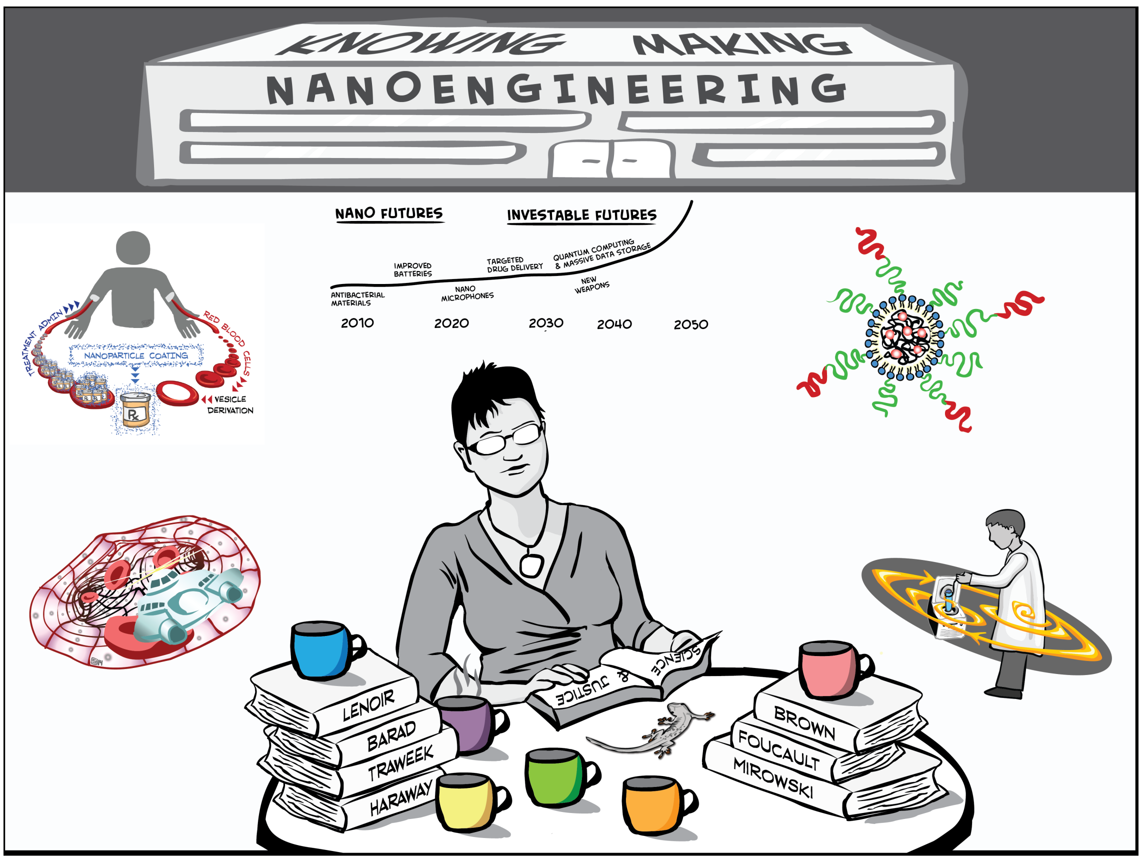

Illustration 141 Examining the disciplinary formation of nanoengineering leads to many complex questions about science and society.

In examining the consolidation of nanoengineering as a disciplinary program, we have encountered many elements that, taken separately, would not appear to be particularly new in the history of Western scientific practices. Certainly commercialization of science and technology is hardly a new phenomenon, corporate influence in the research university is a somewhat redundant phrase, and principles of progress, utility, and individualism are manifest in the earliest moments of Western science. Yet none of these elements are static, independent variables that self-evidently explain or totally account for what nanoengineering is or how specifically it is materializing as an historically contingent constellation of world-making practices.

Let us begin with the primary justification of nanoengineering, the uniqueness of the nanoscale. Because materials at the nanoscale exhibit different properties and

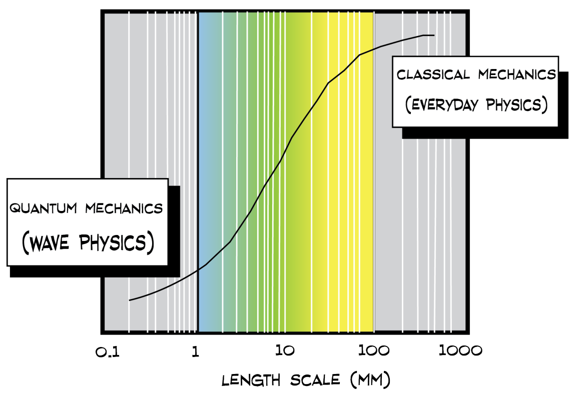

Illustration 142 Nanoscale, between quantum and classical mechanics. Intro II Lecture, 2012.

behaviors compared to their bulk scale counterparts, proponents of this department and disciplinary major claim that the nano world requires unique knowledges and skills, not to mention instrumentation, to understand and exploit it in order to create new technologies.

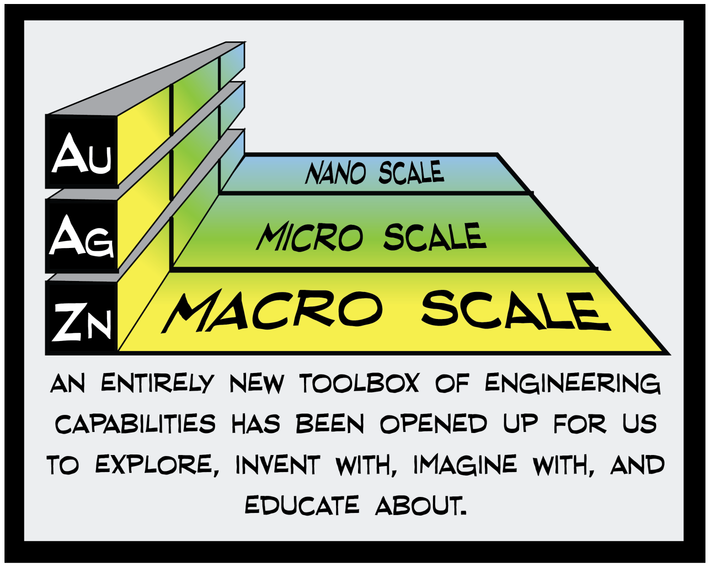

Illustration 143 Going smaller. Intro II Lecture, 2012.

Though a focus on the nanoscale might seem a continuous and logical next step in an historical trajectory of going smaller, manifest in subdisciplines like microbiology, nanoengineering claims to represents a fundamental rupture. Rather than nanobiology, nanochemistry, nanophysics, etc., the nanoscale does not get subsumed into a variety of disciplines; rather, according to nanoengineering proponents, it demands that all disciplines come together at the nanoscale, and therefore naturally become subdisciplines of it. But subsuming otherwise distinct fields under its umbrella is not the only rupture nanoengineering promises. Due to the scalar properties of nanoscale materials and because the nanoscale is a new domain of scientific observation, nanoengineering also claims to transcend other kinds of boundaries—not just those of discipline, but of science and engineering, of basic and applied research, of industry, university, and state, and of natural and manmade worlds. In transcending all of these boundaries to create fundamentally new technologies across nearly every domain, the grand rupture that is promised is one of total industrial revolution and deep societal change.

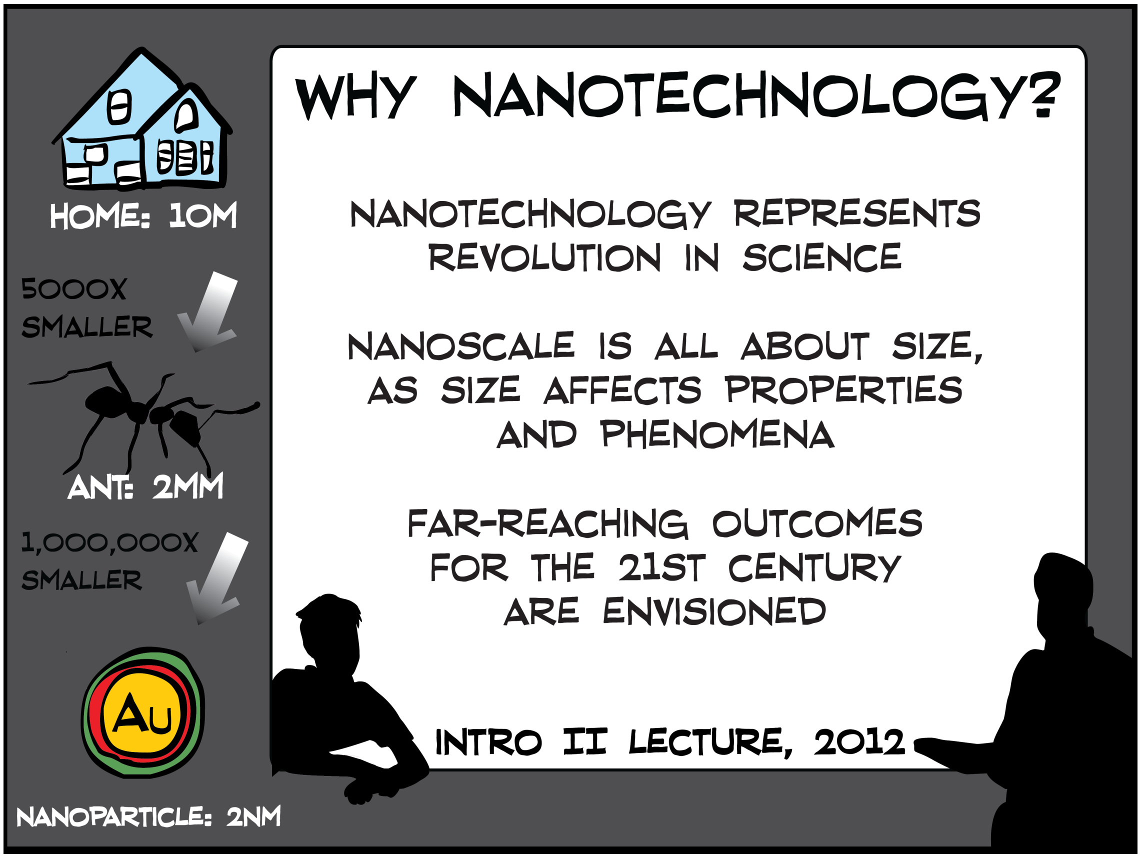

Illustration 144 Nanoengineering "represents revolution." Intro II Lecture, 2012.

We can step back and say these are actor categories, and that there are many motivations for framing nanoengineering in these ways that have nothing to do with the nanoscale per se, not least of which have to do with establishing a distinct field and attracting capital. And I think that would be partially correct but also too quick, simple, even naïve. First, the political economic, ideological, and institutional imperatives to produce capital are not to one side of the emergence and disciplinary formation of nanoengineering. They comprise the very the conditions within which nanoengineering appears, especially if you consider this formation from the 1980s with Don Eigler's 1989 nanoscale IBM logo, President Clinton's establishment of the National Nanotechnology Initiative in 2001, the concomitant establishment of the School of Nanosciences and

Nanoengineering at the University at Albany in 2001, and the establishment of the Department of NanoEngineering at UC San Diego in 2007.

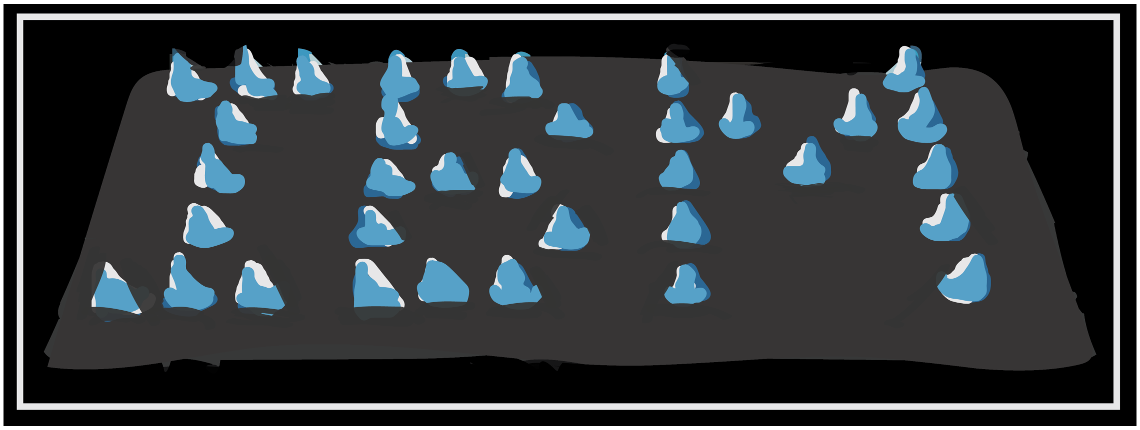

Illustration 145 Don Eigler's IBM logo with xenon atoms.

As I have shown in Chapters 5 and 6, while the institutional imperatives to produce human and intellectual capital are not totalizing, these imperatives do inform the disciplinary formation of nanoengineering and articulate its practices as economic conduct. The constitution of both knowledge production and knowledge workers in terms of capital within this disciplinary program is key to answering the questions of what nanoengineering is and who its practitioners are.

Second, the ways in which nanoengineering understands itself as located at the intersection of multiple categories—of basic and applied research, science and engineering, multiple disciplinary fields, scalar regimes from nano to macro, natural and manmade worlds, and state, industry, and university—and as positioned to translate across these categories is hardly empty rhetoric. As I have shown in Chapters 3 with respect to scale and Chapter 6 with respect to scale and other categories, the nanoengineer's self-conception as a figure who can and must understand and communicate across these boundaries materializes in the department and in the undergraduate curriculum as a defining characteristic of who the nanoengineer is.

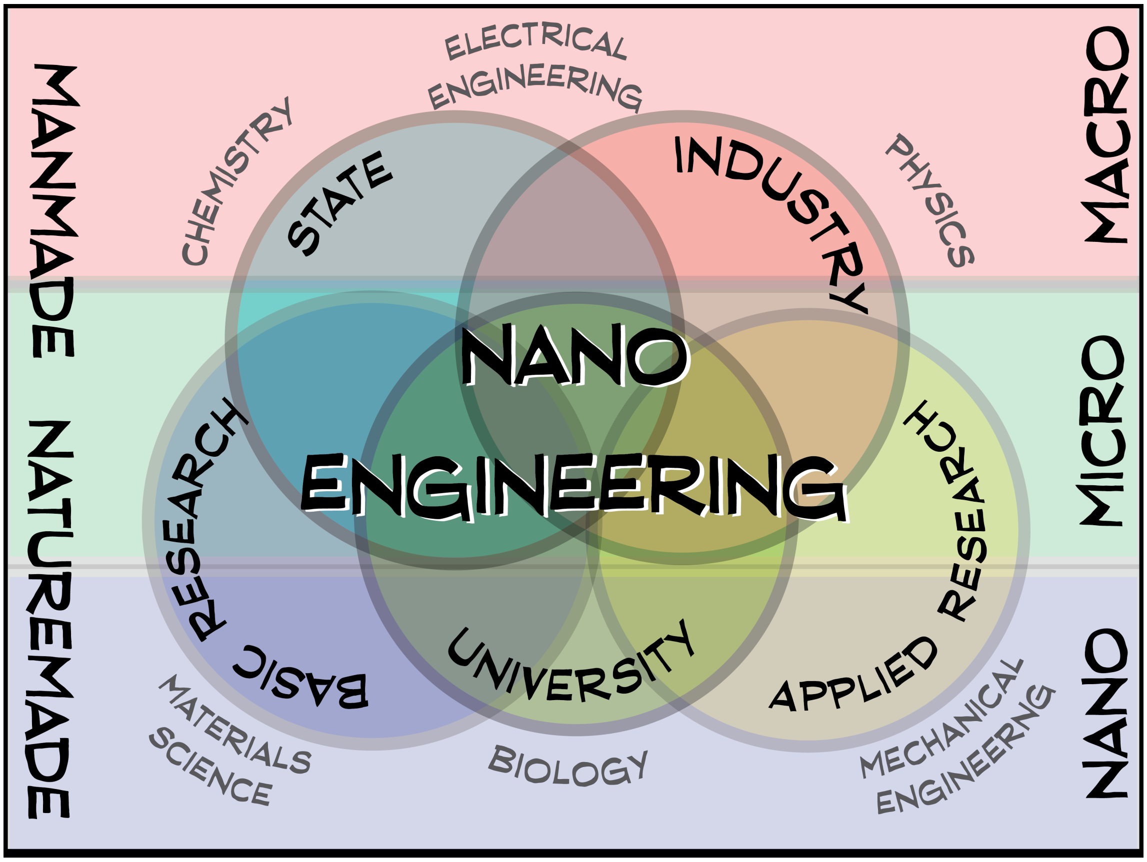

Illustration 146 Nanoengineering understands itself as bridging and in some cases transcending categories.

And, relatedly, innovation too is not to one side of nanoengineering. Nanoengineering is emerging as a field that *is* innovation, and as such, that organizes its research and pedagogy around the necessity of conducting efficient, rational, effective marketization of new processes and products, and of continually optimizing its best practices for doing so. This is not a discipline that has merely adapted to, but has grown up within and been disciplined by the dominant ideologies and imperatives of an innovation economy. To sum up, nanoengineering is being consolidated as a field that exploits the unique properties and behaviors of the invisible nano world; that succeeds and replaces basic and applied research, and science and engineering; that organizes itself as economic conduct with best practices for optimal innovation to the marketplace; that promises useful applications in nearly every domain; that fashions its workers as human capital and its products as intellectual capital; that understands nature as a vast machine of self-organizing autonomous individuals that are fundamentally nanotechnological, and folds nature into its continuum of translation toward the marketplace; and that enshrines its model of the good in the figure of the nanoengineer, whose intrinsically ethical character is evident in her pursuit of nano dreams of societal benefit—a pursuit that simultaneously produces economic benefit which is itself understood as social benefit. In practice, individuals may not adhere to these norms, and the field may fall short of or be at variance with these ideals, but these are the norms and ideals at work in its constitution. Whether nanoengineering ultimately brings about an industrial revolution, however that may be understood, remains to be seen and such a claim may just be the inevitable hype surrounding a new field and its need to define itself and attract capital. But nanoengineering's appearance on the scene as an ideal mode of knowledge production; as a model for aligning the interests of state, industry, university, and citizen relative to production, consumption, education, and globalization; as a rebuttal to the propositions of Vannevar Bush and Cold War era science; as a shrug of disregard to the absence of an Office of Technology Assessment and the impotent regulatory powers of the EPA and FDA; and as a ready salute to the imperatives of competition and capital accumulation, suggests that nanoengineering should hardly be discounted as just more of the same.

Yet writing about nanoengineering from a moment early in its formation is a tricky proposition; its history is one in the making, and any future history of nanoengineering will undoubtedly offer not only different perspectives, but more perspective.

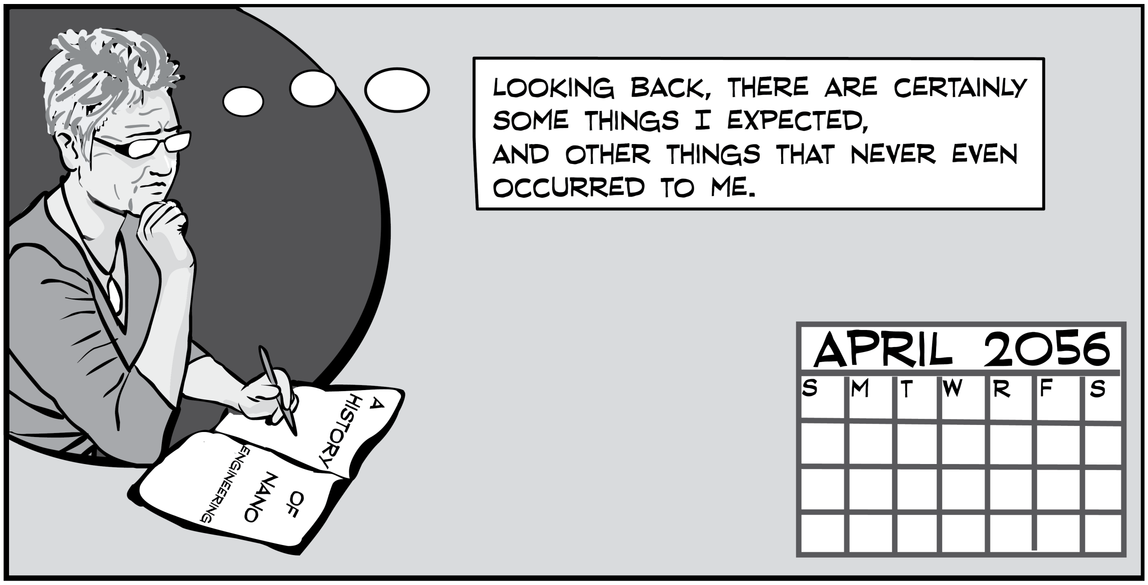

Illustration 147 Looking back, forty years from now.

At the same time, this is a moment in which nanoengineering's future is not yet closed; nanoengineering is not yet blackboxed, and in marketing terms, it may not have reached path dependency. It is even a distinct possibility that fifty years from now there will be no field of nanoengineering, that the term itself may have become archaic, either because the field never fully succeeded in consolidating itself or because it got subsumed into newer fields. But assuming for now that it does prevail as a widely recognized and legitimated field, let me offer two possibilities for its future, each enabled and constrained by the limited perspective I have developed based on this four-year study of a single site of institutionalization. These are future histories that are necessarily speculative, and playfully serious. Science fiction has been an important constituent of this disciplinary formation; so let me use science fiction now to resituate the present in terms of its possible futures.

A Cautionary Future History of Nanoengineering

The first history extrapolates from what I have observed in this site, and represents a cautionary perspective. Nanoengineering will be seen as a field that had its roots in the 20th century Cold War state and Cold War science fiction, with its hopes of technological superiority and domination in war and the fantastical prospects of miniaturization.

Illustration 148 *Fantastic Voyage* imagined shrinking an army to the size of a bottle cap.

With the emergence of new instrumentation that made visualizing and manipulating materials on the nanoscale possible, and amidst a shift in post-Cold War modes of knowledge production, the rise of globalization, the neoliberalization of the state and the university, and the dominance of innovation economics, nanoengineering as a field becomes institutionalized in the early 21st century as one that is intrinsically innovative, entrepreneurial, and good. In places like UC San Diego, college students become nanoengineering majors, and even though they are attending a four-year liberal arts university, their educational path is optimized toward the production of human capital.

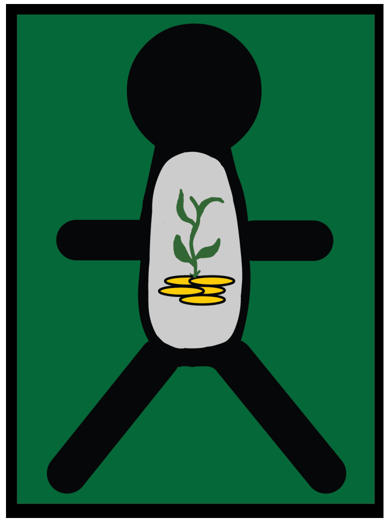

Illustration 149 Human capital.

They learn that to be a successful nanoengineer they need to have an entrepreneurial attitude. But even as they learn to articulate their nano dreams of societal benefit by the time they graduate, in fact most become laboratory technicians on industrial teams, where their labor is invested in corporate innovation and capital accumulation.

As undergraduate students, they are not exposed to critical thinking skills that might challenge or interrogate the technological projects they become engaged in. Their exposure to questions of ethics and responsibility is limited to narrow understandings of professionalism; their professional code prevents them from falsifying data but provides few resources for addressing a range of complex questions: What technological goals should we have? Who and what will and will not benefit? What kinds of social, political, legal, ethical, and environmental implications might this technology have? What kinds of risks, failures, and potential downsides might we reasonably anticipate? Though some will draw on external life experiences that lead them to question easy narratives of universal progress, they are trained to see nanotechnology as unproblematically beneficial. Those who become involved in policy and regulation tend to downplay risk and champion pro-business agendas that support rapid innovation and marketization.

Illustration 150 Professional code of conduct. Students are given a printout of a professional code of conduct. The above text does not draw from a single interview, but sums up the answers I have heard from multiple students when asking them what ethics and responsibility mean to them in the context of nanoengineering. Not a single student has reported to me having been exposed to ethics in the classroom, but they do report hearing that professional responsibility includes not making up data and not knowingly producing something that is faulty or toxic.

Even as highly trained technical laborers, their jobs in industry are never secure, and as full-time jobs with benefits become increasingly scarce, most will work as independent consultants without benefits or steady incomes. As their skillsets becomes more common, particularly outside the United States, their incomes will fall.

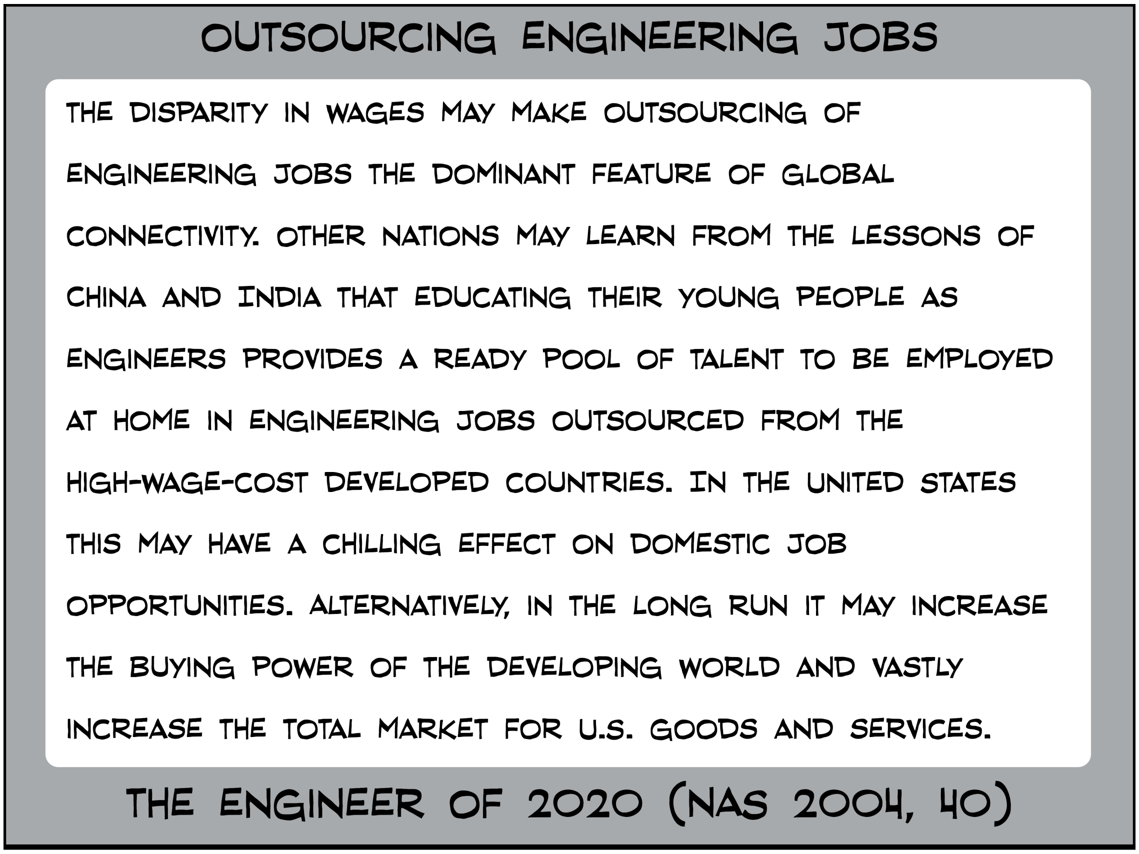

Illustration 151 *The Engineer of 2020* on outsourcing. This report, produced by the National Academy of Sciences, was used by the NanoEngineering Department to guide the creation of the undergraduate major. It discusses the "chilling effect" of potential job outsourcing in an increasingly global environment.

Early pushes in nanotechnology innovation do result in new medical treatments, including highly successful cancer therapies, longer lasting batteries, new solar energy technologies, environmental remediation technologies for oil spills, and new textiles, including light bullet proof materials taken up by the military. These early advances seem to support nanoengineering's claims of technological progress and societal benefit.

At the same time, other developments lead to various crises. For example, the food and cosmetic industries' early adoption of nanoscale materials results in new forms of disease. The widespread use of nanosilver and other nanomaterials in household products, machinery, pipes, and aerosols, results in new forms of environmental pollution and toxicity.

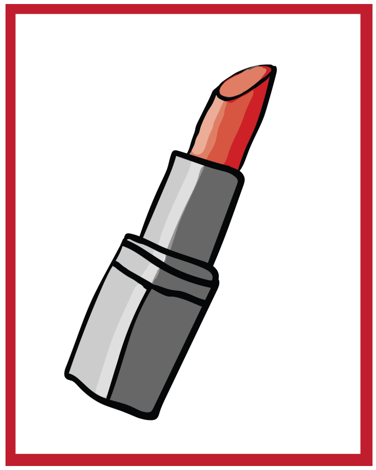

Illustration 152 Nano cosmetics.

Additionally, nanotechnologies create a whole new class of high tech surveillance equipment, from nanoscale tagging and biomonitoring devices to nanoscale camera and microphone technologies that make any expectation of privacy, inside or outside the home, a thing of the past. While nanotechnologies create huge advantages and benefits for some, many of these are unavailable to those who can not afford them, and the negative pollution and health impacts most critically affect those with fewer social, political, and economic resources. Any regulation of nanotechnologies is only implemented after massive failures and catastrophes, and even despite such disasters, often new regulations are not enforced. As nanotechnology instrumentation and knowledges become more widespread, there is also a rise in backyard nanotech DIY production, an area that is entirely unregulated. But as a multi-billion dollar industry, nanotechnologies are ubiquitous, and not as a category controversial. Those nanotechnologies that are controversial are framed by supporters as individual outliers, with the reminder that all new technologies have some risk and that the huge benefits of nanotechnologies outweigh the few problems that have arisen.

In terms of knowledge production, nanoengineering will not be remembered as the first field that took capital accumulation seriously—that honor would go to biotechnology—but it is honored as the first new discipline of the 21st century, and one that signaled a turning point in that after nanoengineering, no new disciplinary formation could successfully consolidate without articulating itself as economic conduct with a direct line toward capital accumulation.

Illustration 153 Future prospects and commercialization efforts. Intro II lecture slide, 2012.

Moreover, though the words "science" and "basic research" are remembered in some circles, by the mid 21st century they have slipped from common usage, and historians look to nanoengineering as one of the first disciplines that insisted these categories were no longer relevant. STS scholars caution against nostalgia for these old terms and against any easy causal explanation for their disappearance, but at the same time claim that real changes in the character and mode of knowledge production did occur around the turn of the twenty-first century that were consolidated by 2050. Over time, four-year programs like UC San Diego's nanoengineering major are increasingly replaced by shorter vocational programs. In order to be competitive with workers from around the world, most students go through two-year vocational programs, which is what is left of public higher-ed, and which equips them to do basic engineering tech work. Those who can afford to go to a private university can pursue one of the many paths toward engineering and venture capital, curricula that generally focus on integrated programs in engineering, economics, and business.

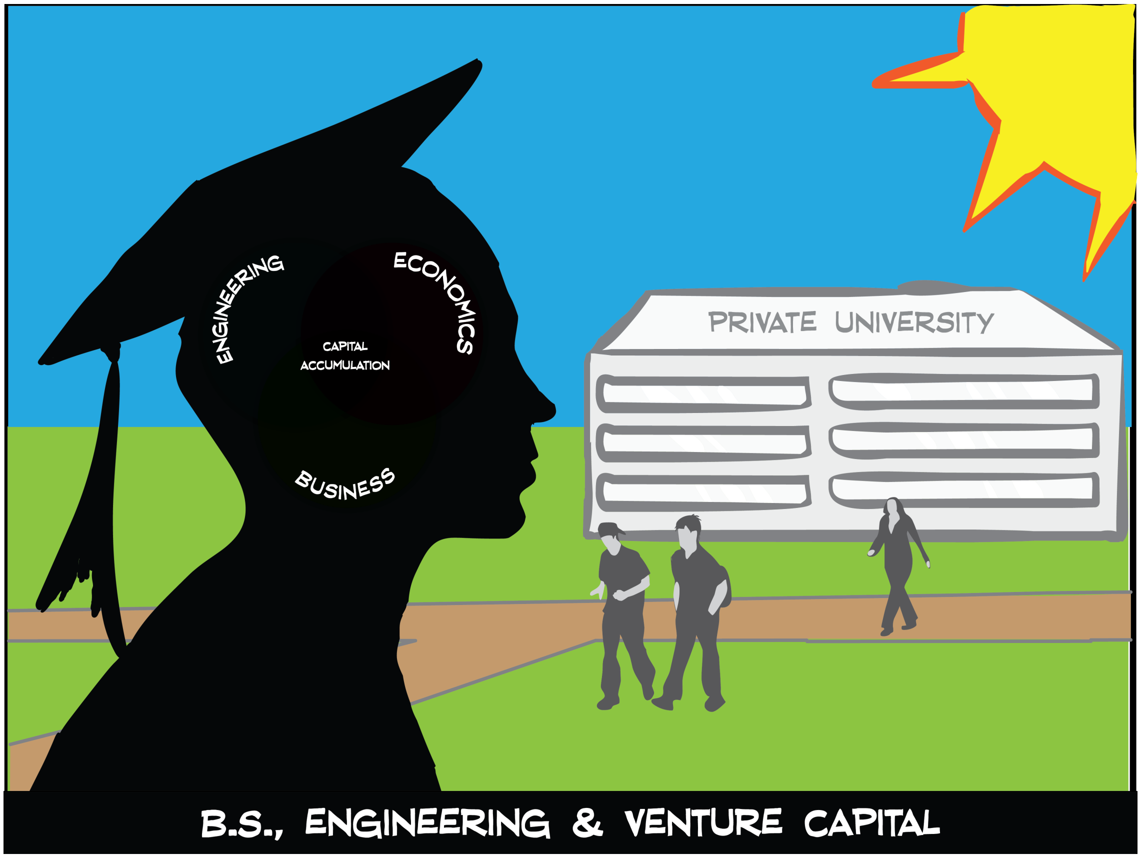

Illustration 154 The future of privatized education.

Maybe. Though I've said this is a cautionary tale, I've hardly sketched out a doomsday scenario. Rather, I've imagined that the tendencies I see in my research site are further solidified and embraced nationally: increased focus on capital accumulation, increased privatization, decreased attention to technological risk or regulation, and decreased attention to producing citizens with critical thinking skills.

An Optimistic Future History of Nanoengineering

Here's another possible history. As more universities look to UC-San Diego's NanoEngineering major, some decide to implement their new nanoengineering programs differently. Attempting to attract diverse students and teach a mode of doing science and engineering that critically engages with questions of ethics, responsibility, and justice, they establish curricula that emphasize the social, political, and environmental dimensions of world-building. They agree that science fiction has a role to play, but they incorporate science fiction into the curriculum not just to articulate the nano dream but to help students engage in complex moral questions raised by the possibilities of nanotechnological innovation.

Illustration 155 *Engineers Without Borders* might inspire such programs. This logo is based on the UK logo. Author invokes fair use of original image.

They agree that nanoengineering is an interdisciplinary endeavor, but they don't stop at considering interdisciplinarity only in terms of related engineering disciplines, such as materials science, bioengineering, chemical engineering, etc. Rather, they want their nanoengineering students to be able to translate across campus divisions, equally comfortable collaborating with scientists, sociologists, STS scholars, and artists.[1] They recognize the political economic realities of nanoengineering, but resist pressure to think in terms of producing human or intellectual capital, and they hire faculty that model

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1. This idea regarding interdisciplinarity being more broadly interpreted comes from a current nanoengineering student, articulated in an informal conversation.

multiple paths toward being successful as a nanoengineer. Where students want to develop entrepreneurial skills and start companies, they are supported, but this is presented as only one possible career trajectory. They agree that all new technological endeavors entail some risk, but they encourage students to imagine potential risk, downsides, and failures with as robust and detailed an imagination as they do when considering potential benefits. They are optimistic about potential benefits, but they encourage students to imagine who and what might not benefit from each proposed nanotechnology, and to consider not just what happens when they realize a nano dream, but what happens over the entire lifecycle of a nanotechnology. What happens when a nanotechnology (i.e., any device that incorporates nanoscale materials or devices into it) is discarded or no longer used? Where do these nanoscale components go? Who is responsible for dismantling and/or ensuring that nanoscale environmental pollution is avoided when nanotechnologies are thrown away or recycled?

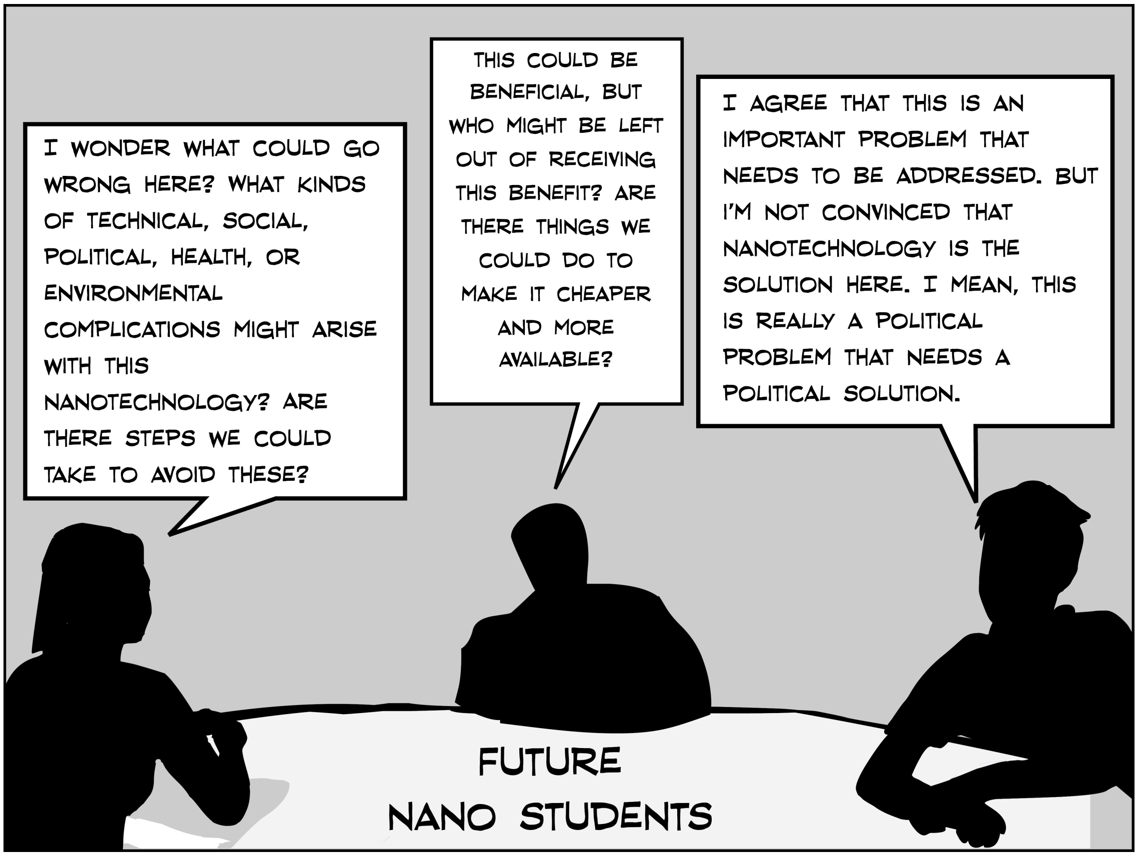

Illustration 156 Nano students of the future, reflexively engaging with their work.

They emphasize that this kind of reflexive, critical, ongoing engagement with science as part of doing science not only constitutes responsibility but will also help them to become more successful in their jobs. After all, if you can identify potential failures, you might avert them. If you can identify who and what might not benefit, you might change course, or identify a modification that would change that outcome. Students not only enjoy learning the technical complexity of working on the nanoscale, they enjoy the moral and political complexity of developing technological solutions to societal problems. After all, they were attracted to an engineering discipline precisely because they hoped to create new technologies that would address societal needs and confer some benefit.

Students learn to recognize when a proposed technological solution will not or should not be pursued as the best way to address a societal problem, and they learn to resist a technofix mentality. Those who go into industry are quick to recognize when a potential complexity is not being adequately addressed; they may be more likely to become a whistleblower too if and when they encounter gross negligence of such complexity. Those who go into policy and regulation become champions of nanotechnology while also developing robust frameworks for assessing benefit and risk. They work to develop methods of democratizing science, and for balancing the needs of business and innovation with the imperatives of inclusion and equality that are central to democracy. Nanoengineering students learn not that smaller *is* better, but that they have an important role to play in addressing questions such as, When, how, and for whom is smaller better?

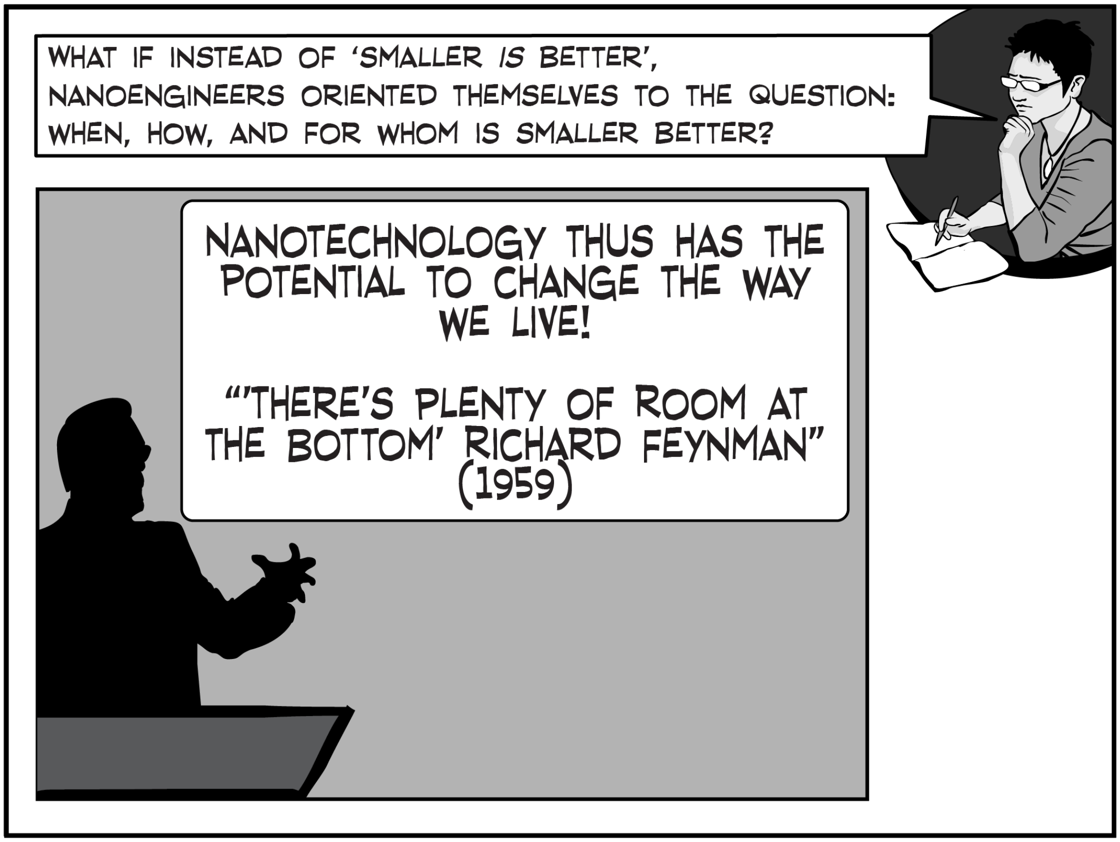

Illustration 157 When, how, and for whom is smaller better?

Students from these programs are particularly successful in whatever career they pursue, and such programs become very popular. Even schools like UC San Diego attempt to modify their program to incorporate more engagement with social contexts. A new generation of scientists and engineers learns to embrace the social, political, and ethical complexities raised by high-tech world-building, and to work on interdisciplinary teams that include scholars and practitioners in the social sciences and humanities. Businesses begin to embrace this version of interdisciplinarity, recognizing that such teams are highly productive and creative, that they create robust innovation rapidly and are more successful at addressing or avoiding social, political, ethical, and environmental problems that would also be bad for business. Funding from both state and industry flows into public universities, and not just for engineering programs, but for programs in the social sciences and humanities as well, and especially for schools that succeed at creating interdisciplinary programs that cut across divisions. At the same time, such interdisciplinary programs are not organized and evaluated in terms of an innovation or business agenda, but rather in terms of their success at engaging local communities and at addressing complex problems. Graduates of these programs are not only extremely successful in their careers because of their training in communicating and working in highly interdisciplinary teams, solving complex problems, and thinking critically, they are also are less likely to lose their job to offshoring because they have complex skillsets that are difficult to replace. In terms of nanoengineering specifically, students are encouraged to engage local communities to identify and consider problems that might be addressed with nanotechnological innovation, rather than just looking to the market to identify market opportunities. When nanoengineers and others apply to the NSF for funding, they not only articulate the possibilities for societal benefit, they explain who and what specifically will benefit, and they also articulate potential risks and downsides. They flag potential social, political, ethical, or environmental issues that might be raised by the research and development they are proposing.

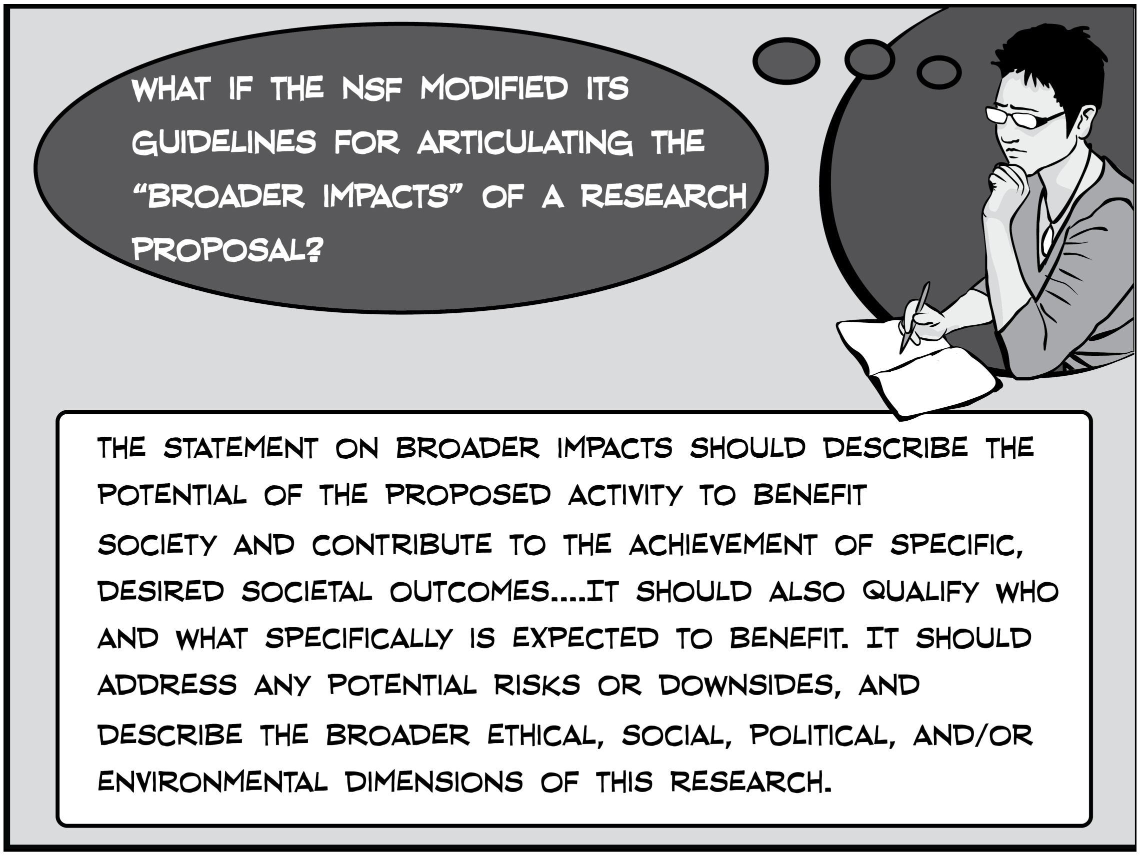

Illustration 158 Imagining NSF guidelines that demand a more complex accounting of "benefit."

World-building Outside the Framework of Utopia and Dystopia

Maybe. Again, just as the first scenario was not dystopian the second is not utopian even if it is optimistic about a real future for those of us in the social sciences and humanities. But discursively, I have still set up a false dichotomy and one that implicitly perpetuates the myth that new technologies that exploit nanoscale behaviors and properties will either be good or bad, and that it is a simple trick to determine which outcome will occur. Certainly what one NanoEngineering department does or does not do will not by itself cause either of these futures, nor is there a set of boxes that nanotechnologists or policy analysts can check off to secure the desired outcome.

And yet there is a reason why my “optimistic” future is weighted so heavily toward the significance of education. How society educates students generally, and how it educates science and engineering students in particular, is of critical importance. I say this not because science and engineering matters more than other disciplinary areas, but because these students, whether they go into the lab or go on to graduate school and eventually run labs, or go into policy and eventually regulate labs, are at the forefront of highly technical world-building that has significant social, political, ethical, and environmental dimensions. Will we just wind them up, or will we try to develop their critical thinking skills so that the ways they pursue their dreams are as carefully considered as the dreams themselves? Is it enough to become capital? Or should we strive to produce scientists and engineers as political members of the polis, who understand that their work is necessarily political as much as it is technical?

In Chapter 2, I argued that cultural objects used in the higher-ed science classroom are politically significant in terms of how they are enrolled in producing an identity and worldview for new members of the discipline. Specifically, *Fantastic Voyage* is used in this department not only to articulate a disciplinary history, but to inculcate in students the nano dream.

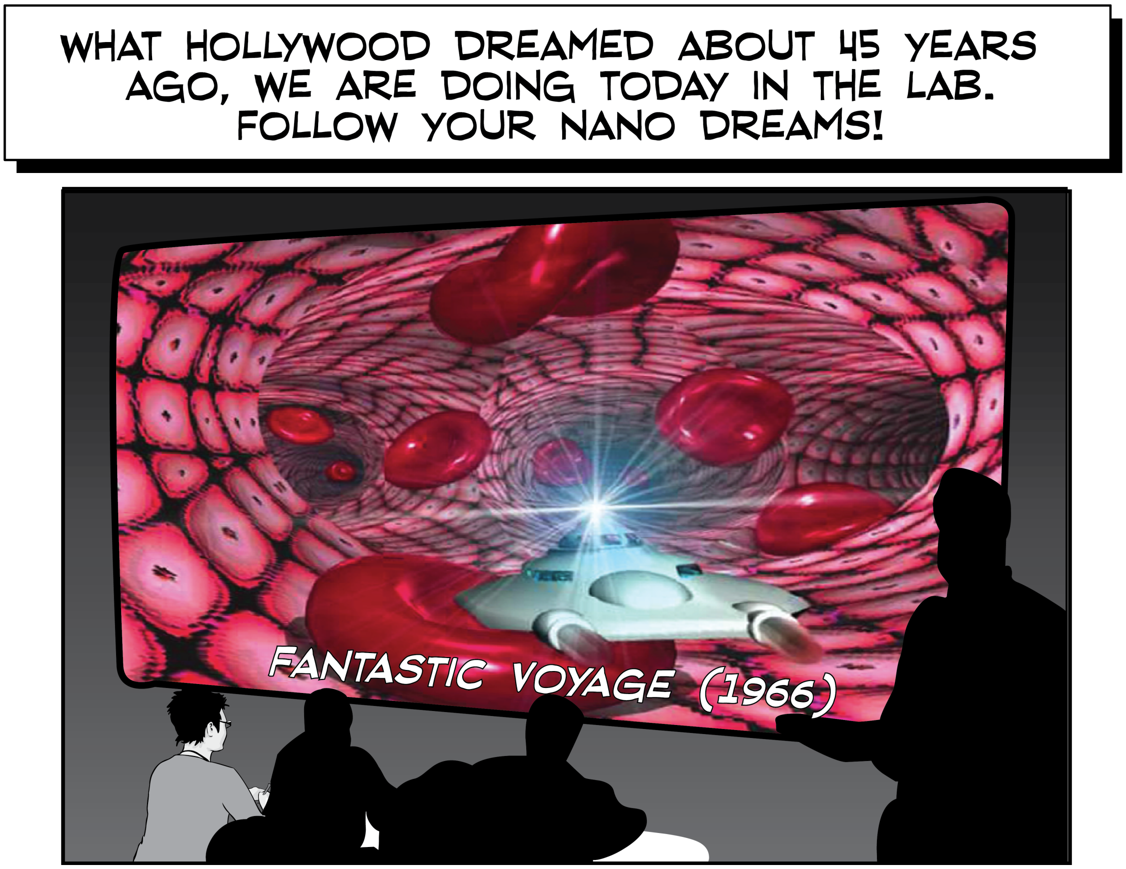

Illustration 159 Follow your nano dreams!

The nano dream is a vision of a future nanotechnology that will benefit society and that should motivate and guide a student's career trajectory. But it's more than that. It is a form of utopian thinking which imagines that nanoengineering ushers in a future with universal progress and benefit, and in fact, that such a future is inevitable. The nanoengineer, as the hero of this story, is intrinsically ethical in part because what she creates heralds this future. Fitting within the either/or paradigm of utopian and dystopian possibilities, the nano dream's constitutive outside—including the nano nightmare but also the multiplicity of possibilities that cannot be easily categorized as simply good or bad—is gestured at but largely discounted. Students are not taught to consider when or why a nanotechnological solution may not be best to address a particular social problem. And they are not taught a mode of critically engaging the many possibilities between the poles of nano dream and nano nightmare. This is emblematized by the ways in which the department frames *Fantastic Voyage*, including the nano dream of miniaturized and targeted medical therapies that save (our) lives and excluding the film's Cold War context and plot line of developing miniaturized and targeted weapons that would kill (other) lives. This framing reinforces the promise of universal benefit through the realization of nano dreams without engaging potential failures, downsides, risks, or exclusions in terms of who or what might benefit.

The complexity of the technical aspects of nanoengineering is thereby aligned with a reductive approach to its social and political aspects. In Chapter 3, I demonstrated how this occurs not only through the use of cultural objects like a science fiction film, but through highly technical lectures in the undergraduate classroom. The categories of "cultural" and "technical" are not so easily distinguished: nanoengineering lectures that draw on a science fiction film to articulate a disciplinary history and identity, and nanoengineering lectures that introduce students to scale are both sociotechnical practices that are constitutive of the nano dream, the nano world, and the nanoengineer. In both sets of practices, the social and political are imbricated in the technical.

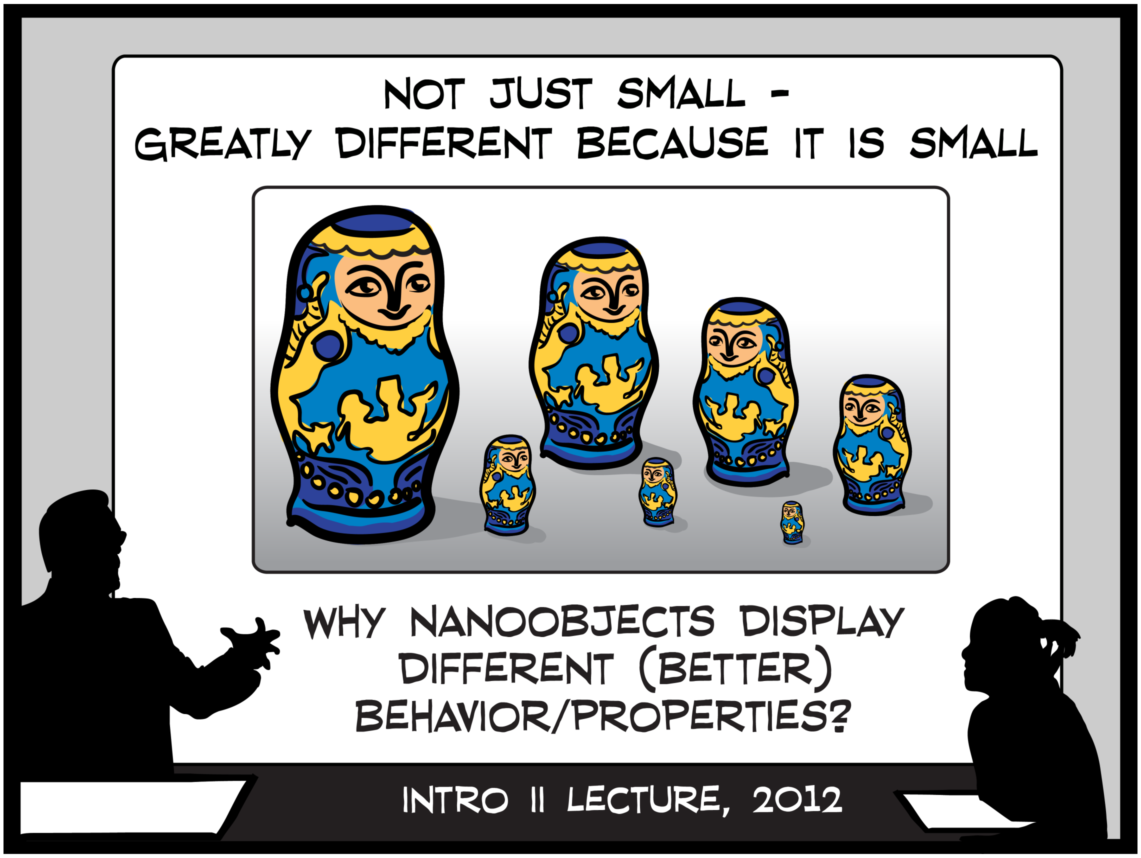

Illustration 160 Smaller, different, better.

In the lectures on scale, even as students learn the "scaling laws" and how to conceptualize and traverse nano, micro, and macro scales, they also learn that smaller *is* better. Without exposure to ways of interrogating when, how, and for whom smaller might not be better, students are implicitly encouraged to make an assumption that could have unintended social, political, and environmental consequences. I suggested that a curriculum that does not teach students how to reflexively engage science as part of doing science deprives them of the critical thinking skills that enable responsible world-building. Moreover, it undermines their ability to successfully engineer nanotechnological solutions because such solutions are always contingent on social and political contexts.

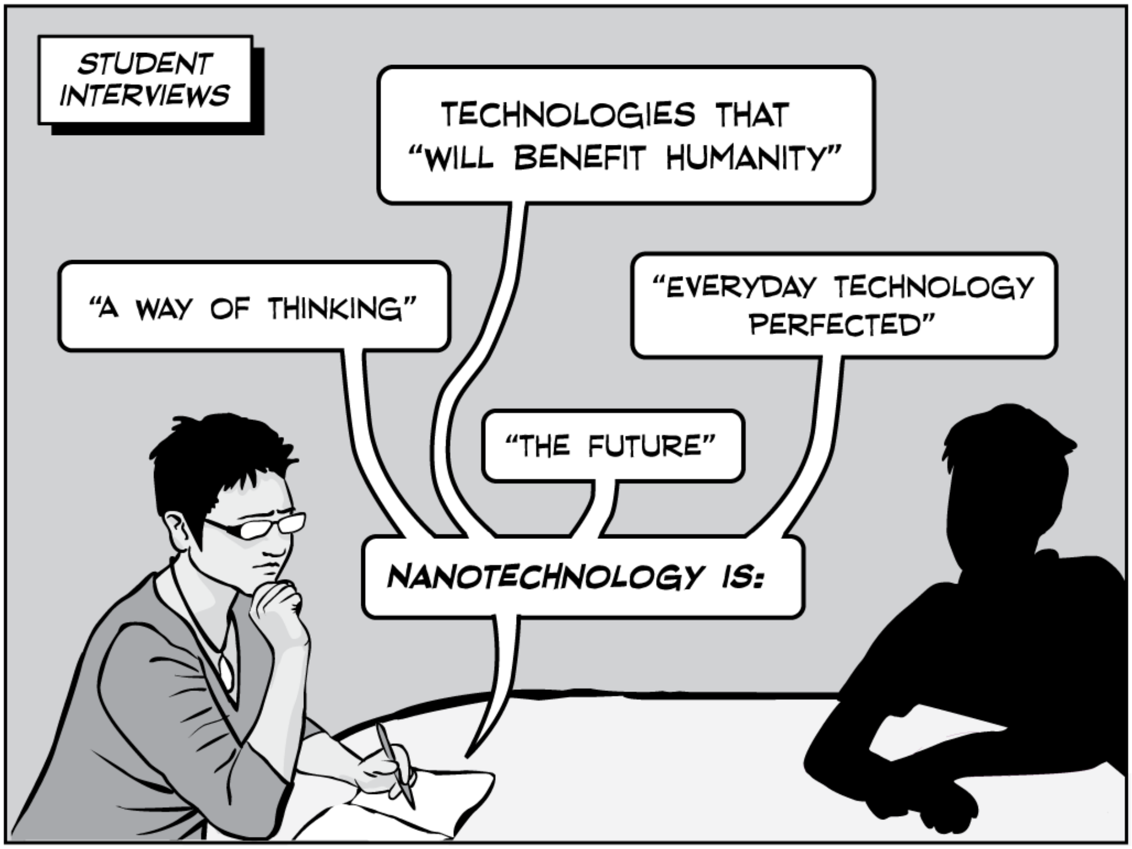

Illustration 161 Understanding nanotechnology as a decontextualized, universal benefit.

Yet, if the overarching goal of an undergraduate curriculum is to produce human capital and to produce the workforce of a new industry, then perhaps a more narrow set of skills fits the bill. In chapters 4 and 5 I looked at how the political economic, ideological, and institutional goals of producing capital and high-tech labor inform the department's approach to consolidating nanoengineering as a disciplinary program. In chapter 4 I explored the material and discursive practices of self-assembly, a nanofabrication approach to building larger structures. I argued that the same assumptions about individualism, autonomy, and self-organization that inform self-assembly in relation to nanoparticles are also at work in expectations about how the nanoengineer should assimilate into the labor dynamics of an innovation economy. In both cases, the unit of analysis is understood as an autonomous individual rationally assembling into larger functional and predictable structures according to information it has, without (outside) human intervention.

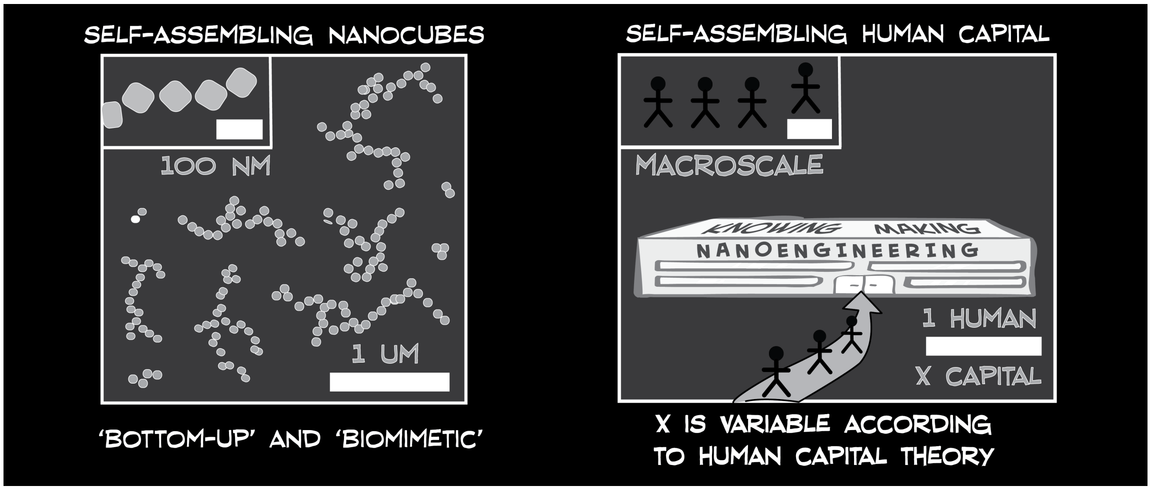

Illustration 162 Self-Assembly, nanoparticles and nanoengineers.

Yet, as I suggested based on my laboratory observations, there is enormous work that goes into creating the conditions such that there is essentially only one possible configuration to assemble into, guaranteeing the predictable nature of the resulting organization.

With nanoengineers too, I pointed to the larger structures that enable and constrain nanoengineering students to predictably assembly into the workforce of the nanotechnology industry. With one model of success before them, that of the entrepreneurial nanoengineer who looks to the market to assess the viability of nanotechnologies, students learn that to be a nanoengineer (or at least a successful one) is to be entrepreneurial. The institutional goal of producing human capital primarily manifests in the ways that students are explicitly and implicitly taught how to be entrepreneurial.

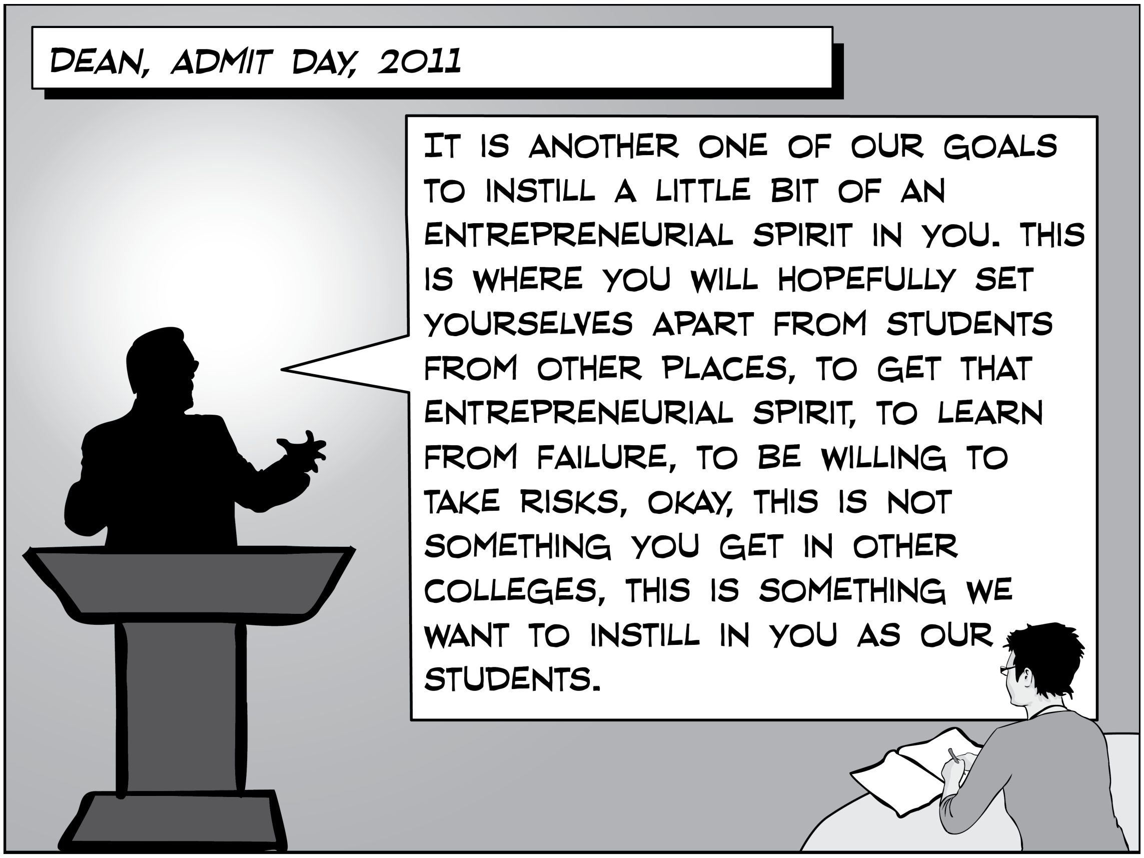

Illustration 163 Entrepreneurial spirit. The goal of producing human capital manifests in the undergraduate curriculum in the emphasis on entrepreneurialism.

Revisiting the trope of the nano dream through the institutional goals of producing human capital and producing a new workforce for a nanotechnology industry gives it a different bent. Aligning students' hopes for pursuing interesting work that will contribute to the common good with the institutional and industrial imperatives of capital accumulation, the nano dream helps to secure a committed worker whose "entrepreneurial spirit" helps to assure her self-assembly into the innovation economy. Though faculty model entrepreneurship, the department expects the majority of its undergraduate students to obtain jobs in industry following graduation. Constituted as human capital, they are expected to become high tech laborers who must continually invest in their capital, who must subordinate their dreams to the imperatives of industrial labor and corporate capital accumulation, and whose ongoing precarity as atomized laborers within competitive, globalized markets is expected and accepted. The lack of critical thinking skills paired with these conditions highlights the prioritization of *homo oeconomicus* and the potential erasure of *homo politicus*. That is to say, learning a simplistic and utopian framework for high-tech progress aligns with a particular version of economic conduct that reduces the political to the economic.

But for those who do on to graduate school, there is potentially a different future, albeit one that still demands that nanoengineering be practiced as economic conduct. Those with a Ph.D. might become entrepreneurial faculty, a CEO of a start-up company, the head of a laboratory, or all three of these positions simultaneously. In this capacity, the nanoengineer is expected to produce intellectual capital. I argued in Chapter 6 that the institutional goal of producing intellectual capital manifests in the department under the guise of "translational research."

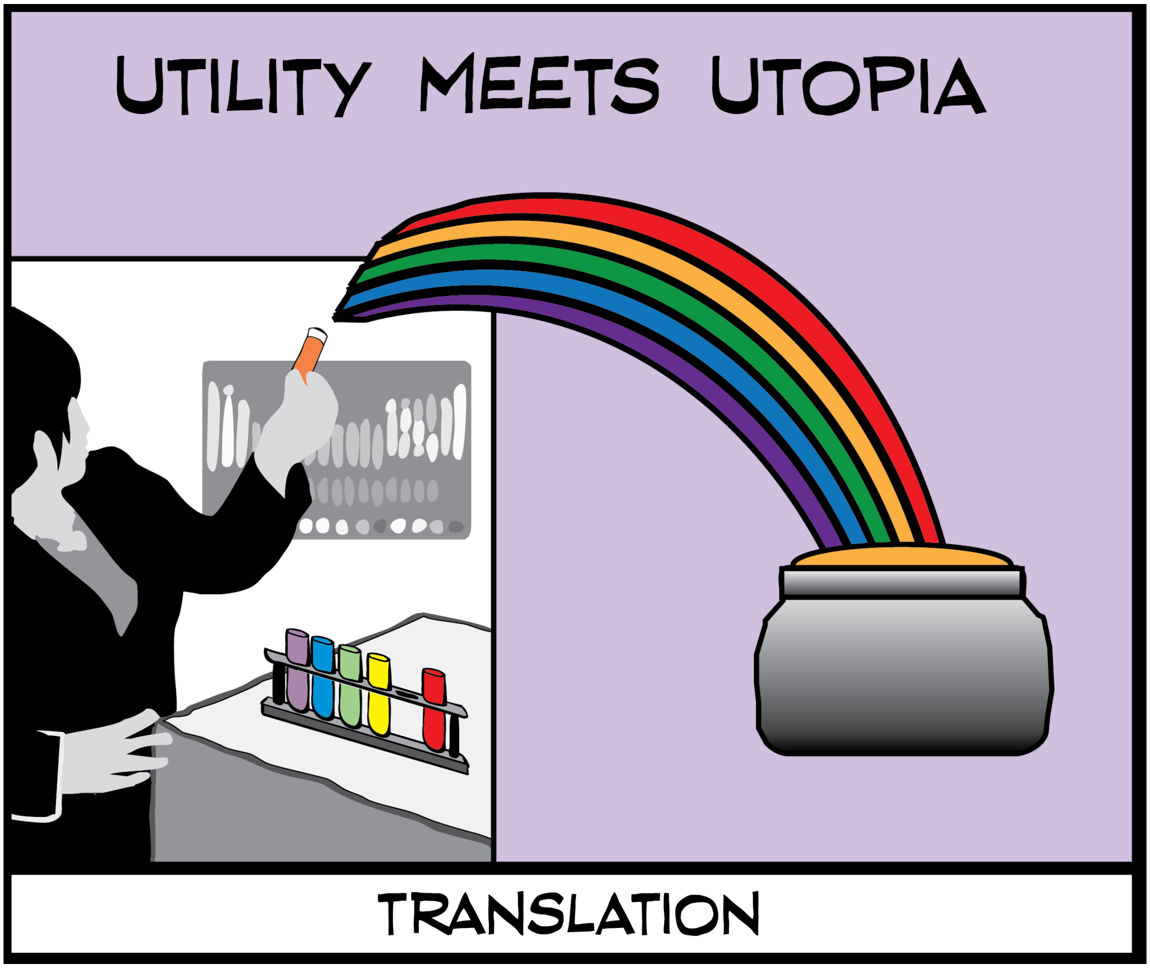

Illustration 164 Translational research.

This is a term that comes from medical research but that is taken up in this department to describe all of nanoengineering research. I argued that it essentially becomes the right tool for the job of consolidating nanoengineering as "innovation for the benefit of society," particularly within an engineering school that demands the production of intellectual capital. Figuring nanoengineering as translational research and the nanoengineer as a translator, it becomes a paradigm of innovation that orientates all research toward the marketplace while making space for basic and applied research and science and engineering, in part by eliminating these categories. It unites the utopian horizon of nanoengineering—its promissory visions of societal benefit—with a utilitarian mode of efficiently and effectively moving new useful processes and products to the market. Indeed, it articulates the utopian horizon of nanoengineering in utilitarian terms: nano dreams must be dreams of things that will be used.

By examining the pedagogical and research practices in one of the world's first nanoengineering departments and undergraduate majors, I have shown how the emergence and institutionalization of nanoengineering is necessarily contingent. Its consolidation as a disciplinary program anticipates and responds to social, political, economic, technical, and institutional dynamics. At the same time, in order to consolidate a disciplinary and professional identity for a new field, this NanoEngineering Department has worked hard to establish a history and a future for the field, and to articulate why nanoengineering is necessary and inevitable, what makes it unique, how it should succeed as a field, and who the nanoengineer is. None of these facets is intrinsic to an ahistorical nanoengineering field; rather, the field is made in places like this department, emerging through the material and discursive practices that answer the implied questions above.

Nanoengineering is being made here as a field that promises to go big by going small. Its proposition of controlling and manipulating the material world is one that is bound up in imaginaries of past and future in which the technical cannot be disaggregated from the social. In the nano dream is not just a promissory vision, but a mode of being and becoming that is shaped by commonsense assumptions about man and nature, science and engineering, politics and economics, the university, the state, and industry. The nano dream contains the nano world, and the nano world is a powerful metaphor.

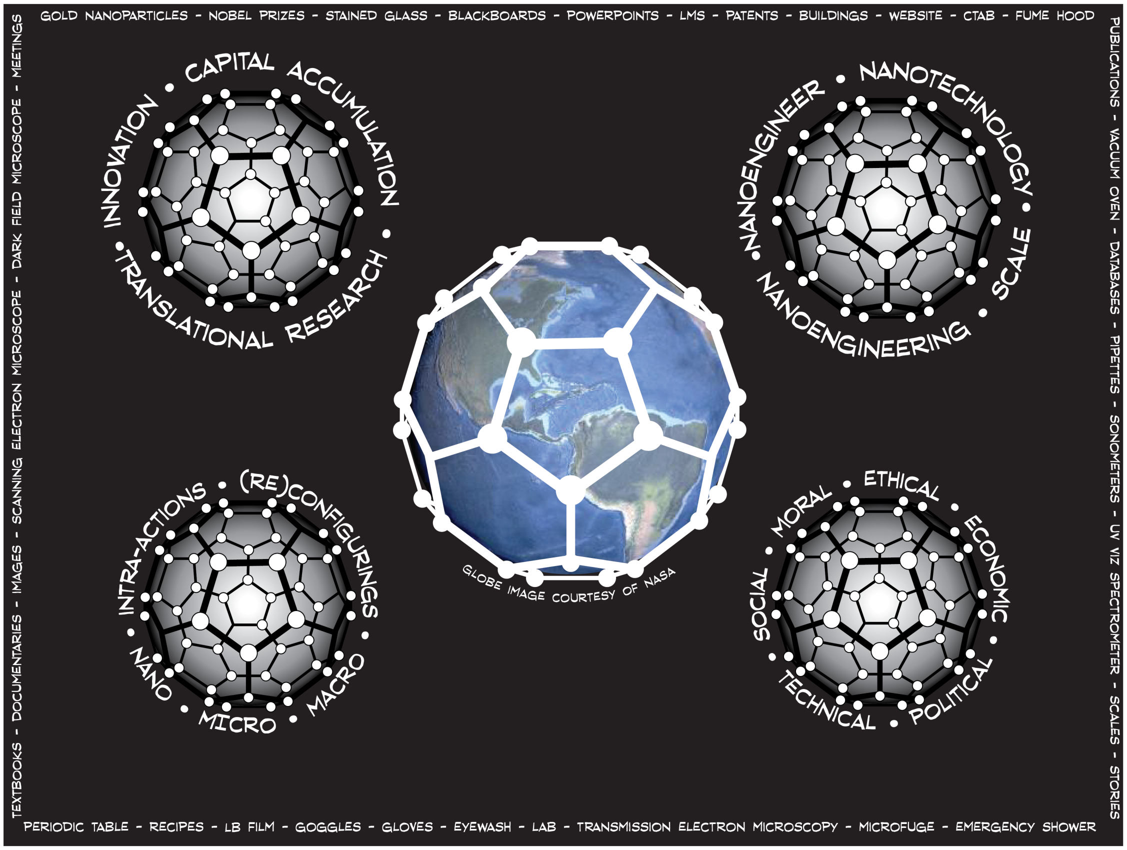

Illustration 165 Nano dreams and nano worlds.