THE NSF CENTER FOR NANOTECHNOLOGY IN SOCIETY AT UNIVERSITY OF CALIFORNIA, SANTA BARBARA

CNS SYNTHESIS REPORT 2016

IRG 1: Exploring Nanotechnology's Origins, Institutions, and Communities: A Ten Year Experiment in Large Scale Collaborative STS Research

W. Patrick McCray, Cyrus Mody, Amy Slaton, & Brian Tyrrell

To Our Readers

The Societal Implications of Nanotechnology: Origins, Innovation, and Risk // Synthesis Reports of the Center for Nanotechnology in Society at UC Santa Barbara

From: Barbara Herr Harthorn, Director, PI, IRG 3 Leader
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UCSB's Center for Nanotechnology in Society (CNS-UCSB), funded by the US National Science Foundation in 2005, constitutes an unparalleled national commitment to research and education intended to enhance responsible development of sophisticated materials and technologies seen as central to the nation's economic future. After more than a decade of funding, CNS-UCSB provides a deep understanding of the relationship between technological innovation and social change, illustrated by an unrivaled set of scholarly, educational, and societal outcomes. These outcomes were largely the work of three main Interdisciplinary Research Groups (IRGs): 1) Origins, Institutions and Communities; 2) Globalization and Nanotechnology; and 3) Risk Perception and Social Response.

In advancing a role for the social, economic and behavioral sciences in understanding and promoting development of equitable and sustainable technological innovation, CNS-UCSB serves as a solid framework for future social science/ science & engineering (S&E) collaborations at the national center scale. Indeed, successful development of the transformative technologies anticipated by the country's leaders depends on systematic knowledge about complex societal as well as technical factors.

Toward this end, each of the three IRGs has generated a Synthesis Report on the cumulative scholarly results and broader impacts of their nearly 11 years of programmatic research, education and engagement.

This synthesis report *on IRG 1* should be cited as:
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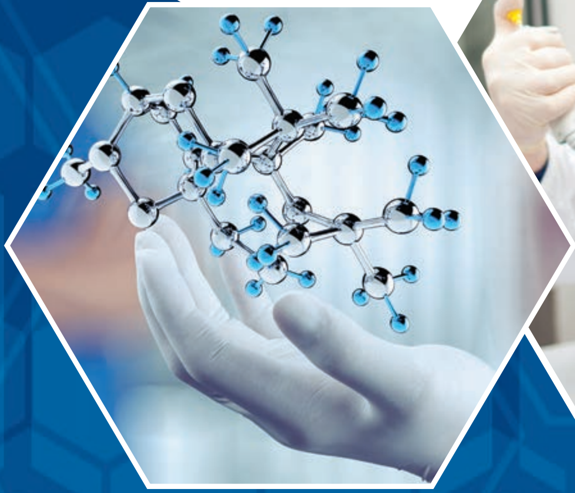


FROM THE OUTSET, IRG 1 FOCUSED ITS ACTIVITIES ON A SIMPLE YET DURABLE ASSUMPTION: RELIABLE KNOWLEDGE ABOUT NANOTECHNOLOGY'S CONTEMPORARY SOCIAL, ECONOMIC, AND POLICY IMPLICATIONS MUST BE BASED ON A CLEAR, COHERENT, AND COMPREHENSIVE UNDERSTANDING OF ITS HISTORICAL AND SOCIAL CONTEXT.

IRG 1: EXPLORING NANOTECHNOLOGY'S ORIGINS, INSTITUTIONS, AND COMMUNITIES

I. Introduction

Shortly after the founding of the CNS, a review in Nature called nanotechnology a "subject with an existential crisis." As a vast, sprawling multi-disciplinary endeavor, the author wondered, what holds it together? Perhaps nanotechnology was simply materials science or physics in a new package. Perhaps even worse, as some cynics suggested, nanotechnology simply offered scientists new paths to secure research funding. A third interpretation was that nanotechnology is constituted by sociological phenomena such as institutions and social networks rather than a unified scientific field of investigation. Questions such as these early in the 21st century about what nanotechnology "really" was and whether or not it radically departed from earlier research initiatives offered a fascinating intellectual stimulus for IRG 1 when it formed in 2005.

"The common belief that we gain 'historical perspective' with increasing distance seems to me to utterly misrepresent the actual situation. What we obtain is merely confidence in generalizations which we could never dare make if we had access to the real wealth of contemporary evidence."

– OTTO NEUGEBAUER,
THE EXACT SCIENCES IN ANTIQUITY
(BROWN UNIV. PRESS, 1957)

Photo: Aerial view of Bell Labs Holmdel Complex

From the outset, IRG 1 focused its activities on a simple yet durable assumption: reliable knowledge about nanotechnology's contemporary social, economic, and policy implications must be based on a clear, coherent, and comprehensive understanding of its historical and social context. This required looking at nanotechnology's history at multiple levels of analysis: scientists' careers, research communities, instrumentation, national and state policy, and the role of public imagination and interest in "visionary engineering" ideas. We recognized that nanotechnology borrowed from people, organizations, and methods that existed before the founding of the National Nanotechnology Initiative in 2000. Those borrowings shaped how nanotechnology is done, perceived, and regulated.

Our primary goal was ambitious. It was an experiment in doing recent history. Through a series of interconnected case studies, we wanted to produce the framework for a comprehensive and holistic narrative of nanotech's historical trajectory. We envisioned this history as a series of narratives that, taken together, would trace the half-century arc of nanotechnology's history. This comprehensive view eventually includes the study of nanotechnology as done in both the physical as well life sciences as well as nanotechnology in a broader global context. We wanted this history to be accessible, valuable and relevant not only to historians, but also a "usable past" that could inform colleagues in other humanities and social science disciplines, as well as scientists, engineers, and policy makers.

This history began with nanotechnology's origins in the communities of physicists, chemists, and materials scientists in the 1950s and 1960s. It then followed key individuals and instrumental developments at places like Bell Labs and IBM in the 1970s. In the 1980s and 1990s, visionaries promoted the future importance of nanotechnology as major discoveries such as the buckyball and inventions such as the scanning tunneling microscope emerged from mainstream

THROUGH A SERIES OF INTERCONNECTED CASE STUDIES, WE WANTED TO PRODUCE THE FRAMEWORK FOR A COMPREHENSIVE AND HOLISTIC NARRATIVE OF NANOTECH'S HISTORICAL TRAJECTORY. WE ENVISIONED THIS HISTORY AS A SERIES OF NARRATIVES THAT, TAKEN TOGETHER, WOULD TRACE THE HALF-CENTURY ARC OF NANOTECHNOLOGY'S HISTORY.

science laboratories. The announcement of major state research and development initiatives in the United States and other countries circa 2001 fostered the creation of a vast transnational infrastructure for doing interdisciplinary research in the 21st century.

Throughout more than ten years of research, we emphasized three interrelated themes: origins, institutions, and communities. We saw these as the critical resources from which scientists, business people, and policy makers fashioned the contemporary nanotechnology enterprise. Broadly defined, these resources included not only scientific and technical knowledge, but also scientific communities and institutions, organizational practices in universities, corporations, and government agencies, and broader context such as international security threats and industrial competition.
Our combined research efforts revealed that, despite its seeming novelty, nanotechnology was and is not a new area of technological development. Rather, it continued and built upon existing institutions, research tools, and discoveries. **Our group paid particular attention to the history of nanoelectronics as a possible path to the continuation of Moore's Law and to the importance of new institutions and interdisciplinary research in nanotechnology.** Seen most broadly, since 2005, our group explored and established the historical contexts for the emergence of nanotechnology as a potent new research field, a central component of American science policy, and a frequent ingredient in popular imaginings of future technologies. At the same time, we remained sensitive to "hidden histories" of nanotechnology that did not appear in the standard narrative of its development. We saw a continual need to move away from the limitations of this basic story toward more complex and nuanced understandings of nanotechnology's past and current context.

For historians and other STS scholars, the study of nanotechnology presented a series of challenges and opportunities. The opportunities derived from the chance to work collaboratively with other historians and with practitioners of other disciplines and to study the emergence of a large-scale technological enterprise. Because much of this story was recent history, we had access to a wealth of evidence not traditionally available to historians. The Neugebauer quote – although written in a different context – that opens this report offers a wonderful justification of the type of work we wanted to engage in. The challenges related, in part, to the nature and preservation of the historical record and in part to the vastness of the subject itself. The ephemeral nature of the documents and sources available sometimes proved problematic – there are no formal archives of nanotechnology for scholars to consult – and required especially creative solutions. This, in effect, made the “first drafts” of history we prepared even more relevant as the sources and evidence we collected will provide research materials for future scholars to use as they revise and add to other work.

DOING HISTORICAL RESEARCH IN A COLLABORATIVE ENVIRONMENT

A traditional feature of historical research, especially in North America, has been the isolated character of its practice. Most articles and books by historians are single-authored as researchers are trained from their doctoral theses onward to own “their” projects with only occasional input from others. IRG 1 departed significantly from this atomized approach, in ways that we hope will establish a model for our colleagues in humanities and STS fields. The Center for Nanotechnology in Society provided a platform and mechanism for doing collaborative historical research in which both the individual projects of IRG 1 members, and the collective efforts of the research group, were accelerated and enriched.

IRG1’s methods combined qualitative and quantitative research. These included exhaustive searches for sources of information, especially primary sources typically found through archival research; the study of the information in those sources; the critical evaluation of the information, an active process to comprehend motives and judge actions; the final synthesizing of material and recasting it according to personal judgment in a narrative.

The group formed in 2005 with just W. Patrick McCray, Cyrus Mody (then at the Chemical Heritage Foundation), and Timothy Lenoir (then at Duke) as the primary members. We steadily added members, initially through connections to Chemical Heritage (David C. Brock, Hyungsub Choi), but later diversified to include historians from other institutions (e.g., Ann Johnson, then University of South Carolina) and approaching history from other directions (e.g., Mara Mills, then at Penn, and Amy Slaton from Drexel). Some people (e.g., Lenoir and Mills) were part of the group and then left; some (e.g., Johnson) had few formal ties to IRG 1 but an outsize influence on our work; some (e.g., Slaton) joined after the CNS renewal and brought important new ideas and life to our collaborations. **During that time, most of the members of IRG 1 were promoted and/or changed institutions, thanks in part to their affiliation with CNS.**

Our collaborations took many forms. We commented on drafts of each other’s articles and books, and in a few cases dyads and triads within IRG 1 co-wrote articles. We wrote grants together, mostly successfully. We organized an international workshop in 2012 on Emerging Technologies and participated in scores of panels at a wide variety of academic meetings. Perhaps our most important research innovation was that we shared archival materials, such that a document by one researcher would be used in an article by another – and vice versa. **Finally, through frequent correspondence, collaboration, and face-to-face meetings in Santa Barbara and at conferences, we each became knowledgeable about each other’s work and perspectives on the histories of science and technology, such that any one of us could present to outside audiences at least an approximation of the expertise of any other member of the group. This kind of networked expertise is common among European historians (e.g., the “Tensions of Europe” project), but almost unheard of in the North American branch of the discipline. CNS made it possible.**

IRG 1: EXPLORING NANOTECHNOLOGY'S ORIGINS, INSTITUTIONS, AND COMMUNITIES

II. Main Accomplishments Over The Life of Both Awards

A. Scholarly Merit - Contributions to Scholarly Knowledge.

Crafting Nanotech Narratives

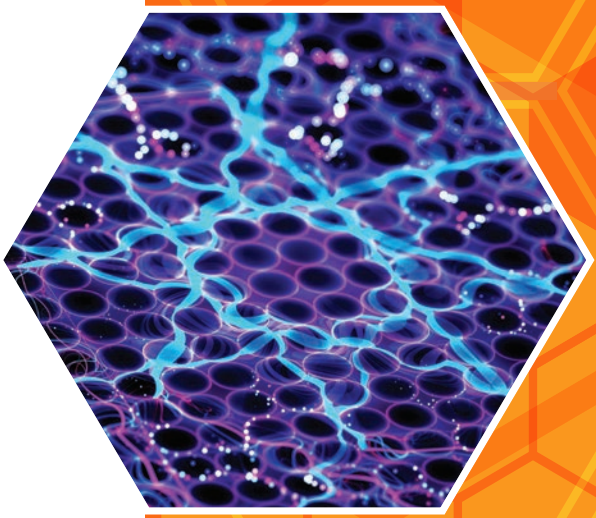
History is a science in a broad, qualified sense, though not an exact science. Its empirical method and reliance on data makes history a type of social science while its drive for critical narratives aligns history with the humanities. History as a dynamic process and interpreting history therefore stands as a story of the past that remains in constant dialogue with the present. Put another way – the history of science is not about studying the state of the scientific enterprise today. Rather it is about understanding how such an enterprise and cultural undertaking came to be in the first place.

Over more than a decade, IRG 1 produced a substantial body of research that offers a broad look at the long history – a period stretching back more than a half century – of nanotechnology. Disaggregated, IRG 1 researchers focused their efforts on discrete parts of this story. To give a sense of the richness and depth of the work produced, we've chosen to highlight four examples.

OVER MORE THAN A DECADE, IRG 1 PRODUCED A SUBSTANTIAL BODY OF RESEARCH THAT OFFERS A BROAD LOOK AT THE LONG HISTORY – A PERIOD STRETCHING BACK MORE THAN A HALF CENTURY – OF NANOTECHNOLOGY.

1. NANOTECHNOLOGY AND STEM EDUCATION

As the U.S. manufacturing sector began to depict nano-scale operations as a viable new option in the mid-1990s, observers in government, economic and education policy centers began to project extensive occupational opportunities for working Americans. These ranged from nano-focused scientific careers in the highest echelons of academic and industrial research, through highly trained technician positions, to jobs centered on the more routine labor of assembly, supply, and maintenance required for all mass-production enterprises. Each type of work was seen to require novel understandings of nano- and micro-scale phenomena and familiarity with special equipment for success either at the lab bench or on the shop floor (both workplaces increasingly being transposed to the cleanroom, a setting with its own special



SLATON'S WORK HAS ANALYZED THE HISTORICAL AND POLITICAL DIMENSIONS OF NANO WORKFORCE PREPARATION ACTIVITY AND ITS CONNECTIONS TO PERSISTENT DISCRIMINATORY PRACTICES IN AMERICAN SCHOOLING AND WORK.

skills requirements). A powerful national drive emerged to create nano-related curricula suited to the preparation of these future members of the nano-labor workforce. Over the last fifteen years, these nano-focused STEM curricula have been devised for the K-12 and two-year and four-year college levels in all regions of the country, arising from individual schools, educational consortia and publishers of STEM educational materials.

The historical nature of nano-related labor and attendant efforts at education have been the central concerns of IRG 1 researcher Amy Slaton, who has investigated in particular the emergence of sub-baccalaureate training for so-called nano-technicians since 1995, a "middle-skilled" workforce stratum projected to fulfill the supposed upcoming needs of American nano-manufacturing in electronics, medical devices, materials and other industries. That far fewer jobs exist in these fields than originally projected is significant, but Slaton's research focuses on the inclusive promises made by such educational programs, more broadly. In many instances supported by the NSF, recent educational research on two-year nanotech programming invokes current ideologies of "STEM diversity," and represents one of many attempts to bring under-represented communities into economic participation in high-tech sectors. Slaton's work has analyzed the historical and political dimensions of this promissory activity and its connections to persistent discriminatory practices in American schooling and work. Additionally, with co-PIs from the Drexel University Department of History, Slaton obtained funding from the National Institute of Standards and Technology (NIST) to hold a graduate summer school at Drexel in 2015. Based in part on nanotechnology case studies, this event convened doctoral students, (including CNS Fellow Brian Tyrrell) to examine the public understanding of technical information associated with nano-related performance and environmental standards. The group critically addressed issues of education, labor and wider societal implications of "nano-literacy" and the role of government and industry in these developments. One result from this research is a book on STEM education and diversity that Slaton is currently finishing.

Photo: Banner from Amy Slaton's blog

2. MICRO/NANOELECTRONICS OVER THE LONGUE DURÉE

Most histories of nanotechnology – whether by journalists, humanists, policymakers, social scientists, natural scientists, or engineers – begin with Richard Feynman's 1959 "Plenty of Room at the Bottom" speech. Those potted histories never acknowledge that the context for the speech was not miniaturization – which Feynman knew little about at the time – but rather, as IRG1 member Joseph November has shown, contemporary debates about computerization of biology in which Feynman participated. Nor do potted histories acknowledge what friend-of-IRG1 Chris Toumey has shown – namely, that the speech almost disappeared from view for more than thirty years.

Not entirely coincidentally, almost all of the very few people who cited Feynman's speech before the late 1980s figure in at least one IRG 1 project. Some of these people, such as Eric Drexler, invoked Feynman to promote wide-ranging visions of technological progress. Most, though, had the much narrower aim of advancing microelectronics development. Some of these early citers of the Feynman speech were primarily interested in forming new scientific communities, such as the fields of microfabrication and molecular electronics. Some were primarily focused on new technologies associated with those fields, such as electron beam lithography. Others promoted new institutions such as academic microfabrication user facilities to build bridges within these communities across disciplines and between universities and industry. In many of these cases, work at the "submicron" level in the early '80s that took inspiration from Feynman's speech evolved into influential early sites of "nanotechnology" in the late '80s and early '90s.

IRG1's approach to nanotechnology through microelectronics has yielded three historical settings that continue to shape what nanotechnology is and how it is done. First, in the early '60s, DARPA established interdisciplinary academic materials science labs that continue to be the template for academic nanotechnology centers. Direct military funding remains an important, if underappreciated, aspect of nanotechnology; perhaps more important, Cold War military models of science policy still reverberate across the institutional landscape of nanotechnology. Second, the 1975 announcement of a Japanese government initiative in microelectronics set off a wave of panicked institutional innovation in American universities and federal agencies. **Many of the leading sites of US nanotechnology research today are descended from those late '70s organizations founded in reaction to Japan's growing competitiveness in semiconductors.** And third, in the early '90s, the Cold War ended, life

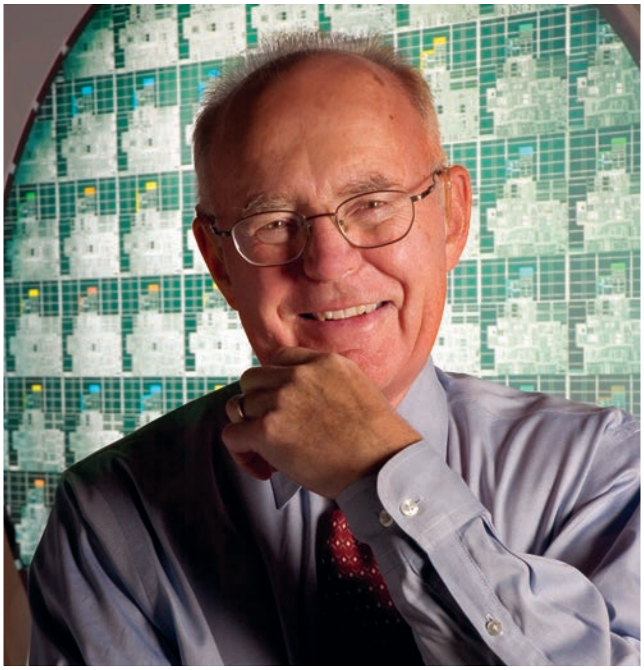


Photo: Gordon E. Moore, Co-founder, Intel Corporation.
Image and caption courtesy of Intel, Copyright © 2005 Intel Corporation.

science funding rose dramatically, and large microelectronics firms shrank their labs. **Many corporate microelectronics researchers moved to universities and forged ties with the life sciences, thereby establishing a template for interdisciplinary, industry-oriented research that still pervades nanotechnology today.** The main investigator for this line of research, Cyrus Mody, has recently completed a book manuscript based on his work called *The Long Arm of Moore's Law*.

3. NANOTECHNOLOGY AND THE PUBLIC IMAGINATION

Paradigmatic histories of American technology have often noted that "technological enthusiasm" – often possessing a utopian strain – is one hallmark of the modern American experience. Nanotechnology was no exception. This line of work has investigated historical cases and explores how public perceptions of nanotechnology were influenced by its connections with earlier expressions and advocacy of technological enthusiasm in the 1970s, and expressions of technological enthusiasm, ideas about technological utopias, and how public imaginings of future technologies have intersected with public policy. During the 1970s and 1980s, futuristic technologies including nascent ideas about nanotechnology stimulated the creation of privately funded research institutes and investment from high-tech entrepreneurs. While some of these futuristic visions (including those for early forms of molecular manufacturing/engineering) may seem unusual today, they were taken seriously at the time and, as McCray argued in his 2013 book *The Visioneers* – a work made possible by CNS – had some degree of influence over public perception and public policy. By examining the political and social

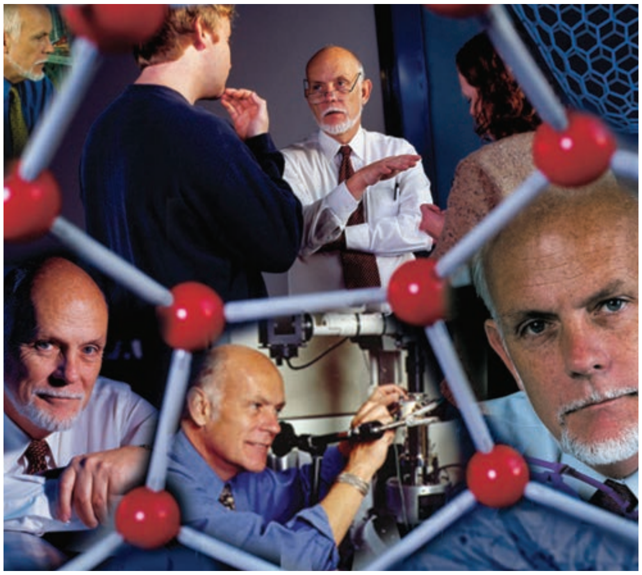
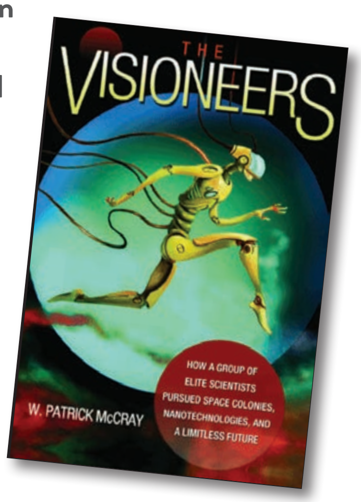


Photo: Nanotechnology advocate Richard Smalley won the 1996 Nobel Prize in Chemistry for the discovery of a family of carbon molecules called fullerenes, including the "buckyball."

Credit: Photos from Rice University, image courtesy of the National Science Foundation context of several exploratory or even fringe technologies – the distinction often rests with the beholder – and the communities of the scientists, technologists, and futurists who advocated them, this work explicated a clearer understanding of how modern technological utopias emerges. **This story is relevant not just for understanding how radical new technologies are proposed but also how the public and media engage, accept, and reject them. By virtue of their impact on people's expectations for what tomorrow's technological future would hold, our research has explored how these visions played a role in shaping public imagination and perhaps feeding a cycle of anticipation, excitement, expectation, and disappointment.** By considering a range of interrelated exploratory technologies, including nanotechnology, we have developed a better understanding of how people imagined the technological future and how these expectations changed over time.

While skeptics saw radical ideas for nanotechnology – ideas like Eric Drexler's designs for molecular assemblers – as hubristic hallucinations expressed by an over-technological society, a fundamental historical fact remains: **Whatever disappointments and disenchantments follow in their wake, these visions of utopias built on ideas from the frontiers of technology fascinated scientists, the media, and the public. At the same time, actors in *The Visioneers* had to establish credibility against detractors who labeled their work, as one critic said, "part of the boundless freak show of technological optimism."** Despite the darker visions that accompanied these futuristic visions and their dubious claims to success, exploratory technologies from the 1970s and 1980s attracted many believers. By virtue of their impact on people's expectations for what tomorrow's technological future would hold, these visions also played a large role in shaping the public imagination and perhaps feeding today's all-too familiar cycle of anticipation, excitement, expectation, and disappointment when it comes to emerging technologies.



The Visioneers
(W. Patrick McCray)

4. DNA NANOTECHNOLOGY

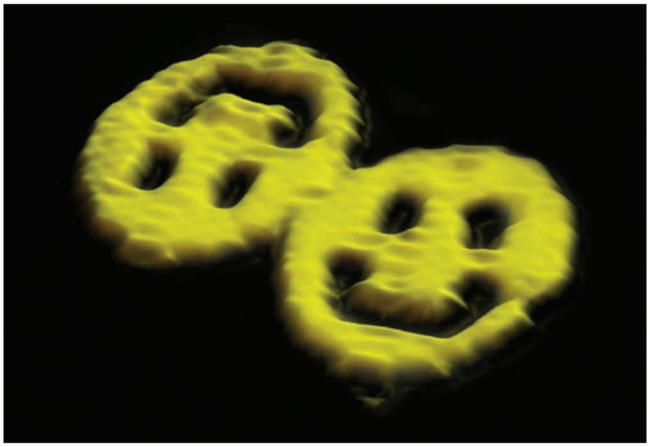
The 16 March 2006 cover of Nature depicted a smiley face that appeared strangely textured and slightly irregular. The headline identified the image as DNA origami – a structure made entirely from the genetic molecule – and proclaimed that this represented a way to make "nanoscale shapes the easy way." Paul Rothemund, a Caltech researcher, used E. coli DNA as the base of his shapes. He exploited the tendency of DNA bases to bond with one another predictably to fold the DNA strand on itself. Then he used shorter strands of DNA to hold the shape stable. Rothemund's DNA origami technique allowed researchers to create hundreds of millions of nano-scale structures in any shape they wanted. The Nature cover announced the maturity of structural DNA nanotechnology, a field that emerged after the 1980s. DNA origami offered an alternative to the laborious methods

RESEARCHERS COULD THINK ABOUT THE MOLECULES AS BRICKS RATHER THAN BLUEPRINTS, AND DNA BECAME AN ENGINEERING MATERIAL.

and strict assumptions then popular with DNA nanotechnologists. DNA origami transformed the field of structural DNA nanotechnology from an artisanal craft to an industrial process. The mass production of DNA nanostructures relied on technologies developed during the Human Genome Project (HGP): machines for sequencing and synthesizing DNA.

For more than two years, IRG 1 researcher and CNS Graduate Fellow, Brian Tyrrell, studied the effects that the commercialization of HGP technologies had on the field of structural DNA nanotechnology. Sequencers read the precise ordering of DNA's base pairs, and synthesizers could create custom sequences of DNA. Between the early 1980s and 2006, the cost of ordering DNA from commercial suppliers declined precipitously, and researchers from fields including chemistry, physics, and computer science found easy access to custom-made DNA strands. The interdisciplinary approach conceived by these researchers led to a reevaluation of DNA. Researchers could think about the molecules as bricks rather than blueprints, and DNA became an engineering material. With new laboratory practices, the multi-disciplinary researchers who populated the discipline developed techniques to create increasingly elaborate structures using DNA. DNA nanotechnology researchers focused their energy on scaling up the production of DNA nanostructures by creating programs to streamline their design. Using DNA from commercial suppliers, researchers created a system of mass-produced nanostructures.

Tyrrell's research suggests a continuity between the HGP and later federal initiatives funding nanotechnology research.



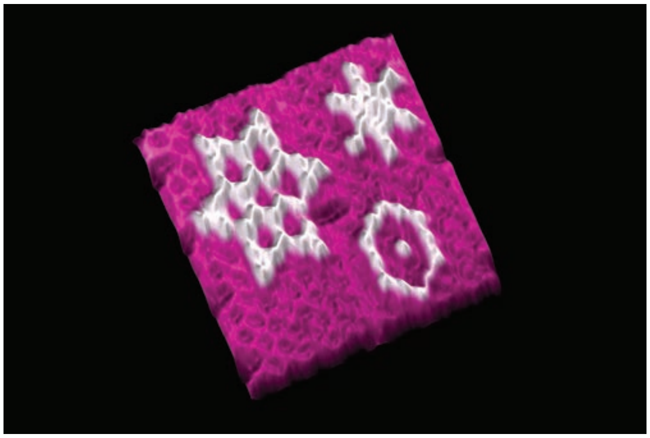


Photo: These nanoscale smiley faces and snowflakes were created by Caltech researcher Paul W. K. Rothemund via the technique of DNA origami.

Courtesy of Paul W. K. Rothemund and Nick Papadakis

Just as all of the main researchers associated with IRG 1 came to the CNS with nanotechnology's history already on their research agendas, so they intend to continue these lines of investigation after CNS concludes. For example, Cyrus Mody and Amy Slaton both have book projects underway that explore the long history of electronics and the question of diversity in STEM education, respectively. Meanwhile, CNS Graduate Fellow Tyrrell, in conjunction with IRG leader McCray, intends to present and publish results from his work on DNA nanotechnology after CNS wraps up.

Given our goal of creating a broader and more synthetic narrative of nanotechnology that spans a multitude of countries, political economies, and laboratories, it seems somewhat artificial to turn around and take a "reductionist" stance that disrupts this cohesiveness. However, we are mindful that such nuggets are of use to our colleagues and policy makers. Therefore, we offer a selection:

- Nanotechnology did not emerge *ex nihilo* as an American research initiative circa 2001. Rather, it was the culmination of years of research and investment – much of it sponsored by federal agencies – that created an extensive suite of available and accessible tools, expertise, and communities.
- Much of today's current nanotechnology infrastructure exhibits what a sociologist would call institutional isomorphism. Centers and research laboratories are built on preexisting models and templates of what has (and hasn't worked) in other areas of research such as materials science. For example, NSF began funding multiple waves of academic centers. One of the first of these, Cornell's National Research and Resource Facility for Submicron Structures, became a crucial driver in the creation of nanotechnology institutions in the '80s and '90s.

OUR WORK ON SPINTRONICS – AN AREA OF CONTEMPORARY RESEARCH THAT WAS CRITICAL TO THE FURTHER MINIATURIZING OF COMPUTER HARD DRIVES IN THE 1990S AND WHICH SERVED AS THE BASIS FOR THE 2007 NOBEL PRIZE IN PHYSICS.

Photo: Spintronics led to enhanced storage capacities, enabling devices like the iPod.

TYRRELL'S RESEARCH SUGGESTS A CONTINUITY BETWEEN THE HGP AND LATER FEDERAL INITIATIVES FUNDING NANOTECHNOLOGY RESEARCH.

- There is very little new knowledge in nanotechnology today – i.e. knowledge that is different from (or would not have been created by) more traditional fields like chemistry, materials science, and electrical engineering. The hope of supporters, though, is that by creating these new *institutions* now, new *forms of knowledge* will emerge down the road.

- The complex nature of technological ecosystems translates into a variety of actors essential for successful innovation. One species is the *visioneer,* a person who blends engineering experience with a transformative vision of the technological future and a willingness to promote this vision to the public and policy makers.

- Although it is often elided in historical accounts and present-day studies of nanotechnology, our research has shown the central importance of the micro/nano electronics industry to the development of nanotechnology as a research enterprise over the last half century. Our work on spintronics – an area of contemporary research that was critical to the further miniaturizing of computer hard drives in the 1990s and which served as the basis for the 2007 Nobel Prize in Physics – demonstrated its transition from a laboratory-based basic science discovery made in 1988 to a field funded by DARPA and other military agencies to one which is supported by university-corporate partnerships. Work such as this enabled us to discover "hidden histories" of nanotechnology and illuminate changing relationship between science/technology and academe/industry.

- Documenting the history of emerging technologies is an exceedingly difficult task. Often there are no formal archives for the historian or STS scholar to turn to. One often-overlooked outcome of IRG 1 work is both uncovering as well as preserving essential historical materials that will be valuable, we imagine, for both future scholars as well as policy makers keen to understand a past research initiative. These include the collection of dozens of oral history interviews as well as the permanent preservation of research materials used by IRG 1. For example, IRG 1 leader McCray donated 17 boxes of collected archival material to Stanford University's Special Collections in 2016.

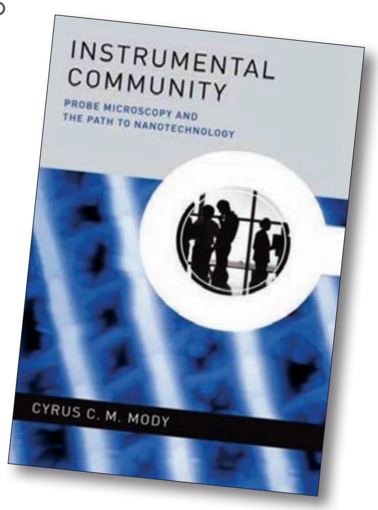
B. Outcomes and Broader Impacts.

Accomplishments

Metrics offer an approximate way to evaluate the success of a research effort. But, in the case of IRG 1, they are nonetheless impressive. Over the course of CNS's activity, researchers from IRG 1 – the smallest of the Center's working groups – published 100 articles, essays, and books. Its members also gave over 200 talks, speeches, and panel appearances, reaching a diverse set of international audiences on an array of topics connected to the historical and contemporary aspects of emerging technologies.

In the humanities, **books still remain the gold standard against which to judge scholarly merit. Books represent the distillation of years, sometimes decades, of scholarly activity, trenchant thought, and careful writing. Included in the list of IRG 1's publications are several single author monographs that either appeared during the decade CNS was active or which will appear shortly.**

Two of these stand out: Cyrus Mody's book on the history of the scanning tunneling microscope, *Instrumental Community: Probe Microscopy and the Path to Nanotechnology*, won two prizes – the 2013 James T. Cushing Memorial Prize (for significant work by younger scholars in the history and philosophy of science) as well as the Paul-Bunge-Preis given by the German Bunsen Society for Physical Chemistry. Traced through the vicissitudes of government investment in basic research, Mody's story explains how the work done by this community gained the label of "nanotechnology" and became a priority for federal funding. Likewise, W. Patrick McCray's *The Visioneers* won two prizes – the Eugene E. Emme Award for best book from the American Astronautical Society as well as the Watson and Helen Miles Davis Prize from the History of Science Society.



Instrumental Community
(Cyrus C.M. Mody)

Both of these books reached the publication stage because of support from CNS. Books and articles are one way to reach the scholarly community. In 2013, IRG 1 tried another path. McCray, working with Mody and Ann Johnson, organized a two-day workshop around the theme of "emerging technologies." To our knowledge, this was the first such exploration of this important topic from the perspective of historians of science, business, and technology. The workshop was based on more than a dozen article-length pre-circulated papers from a carefully chosen group of scholars – some from the U.S. and some from overseas – who were at different stages of their academic careers. Added value came from our commentators: Ron Kline and Michael Lynch (Cornell), Sarah Kaplan (Univ. of Toronto), Amy Slaton (Drexel), Bill Leslie (Johns Hopkins), and Martin Collins (Smithsonian). Kline was a past president of SHOT; Lynch a former editor-in-chief of *Social Studies of Science*, and Collins the then-editor of the journal *History and Technology*. For students and postdocs at the workshop, this was an opportunity to not just engage with the topic but also to interact one-on-one with leading figures in the community's publishing wing.

The workshop's goal was to develop a historical framework in which to understand the often-problematic category of "emerging technologies." We defined emerging technologies as those which are described (now or in the past) as technologies or technological systems that will "change the game," driving new markets, requiring new regulatory paradigms, and having broad and difficult to anticipate social "impacts." They are often associated with risk, speculation, uncertainty, and the possibility of financial reward.

THROUGHOUT IRG 1'S LIFESPAN, ITS MEMBERS MADE A CONCERTED EFFORT TO CONNECT THEIR SCHOLARSHIP TO A DIVERSE SET OF AUDIENCES.

THE SUCCESS WE HAD IN THIS EFFORT IS BORNE OUT BY BOTH THE NUMBER AND RANGE OF VENUES IN WHICH WE PRESENTED IN OUR WORK.

One important outcome of the workshop was to complicate the notion of emerging technologies by highlighting technologies which have already emerged, failed to emerge, or matured without ever being proclaimed as "emerging." By examining the history of several specific once-emerging technologies, this workshop both clarified and elaborated on the entire category.

Another workshop was convened in 2015 by Amy Slaton. Funding from the National Institute of Standards and Technology (NIST) supported a two-week graduate summer school at Drexel in July 2015. Based in part on nanotechnology case studies, this event convened doctoral students to examine global, historical understandings of performance and environmental standards. The group considered societal implications of "nano-literacy" including public responses to nano-related education initiatives and consumer understanding of standards for the safety of nano-pharmaceutical products. An online platform and follow-up workshop on the Critical History of Standards currently continue the work begun in the summer school.

Workshops offered one means to connect IRG 1 research to a select part of the scholarly community. Presentations, invited talks, public appearances, and so forth were another. Audiences ranged from local community organizations to international meetings of physicists to historians of science and technology to attendees at the World Economic Forum in Davos, Switzerland.

We reached a different community through our teaching and pedagogy. Like our other efforts, these efforts targeted a diverse audience. All IRG 1 members with academic and teaching appointments used CNS-derived research in a multitude of classes – from specialty courses on the history of emerging technology to more general undergraduate survey courses on the histories of science and technology. Outside of the classroom, our pedagogical work extended outward to mentorship of undergraduate interns as well as graduate student research fellows as discussed in the previous section.

Photo: McCray delivering a talk at the World Economic Forum in Davos, Switzerland.

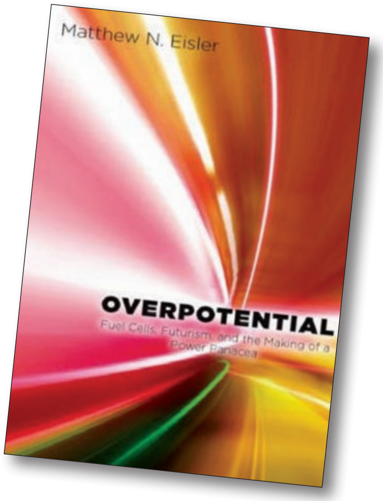
Professional Development for Students

In addition to its research, IRG 1 provided professional developments and research opportunities for undergraduate and graduate students as well as postdoctoral and visiting scholars.

Between 2005 and 2016, four graduate students who had CNS fellowships were associated with IRG 1. Three of these – Mary Ingram-Waters, Summer Grey, and Roger Eardley-Pryor – completed their degrees. A fourth, Brian Tyrrell, will finish his Ph.D. in 2017. Ingram-Waters is now an assistant professor at Arizona State University; Eardley-Pryor is a research postdoc at the Chemical Heritage Foundation. In addition to these graduate students, a number of undergraduate students assisted IRG 1 research. Finally, Matthew Eisler worked at CNS for 2-plus years as postdoctoral researcher. During this time, he authored a number of publications and also completed a book (*Overpotential*, Rutgers, 2012) about hydrogen fuel cell technology.

In addition to the students who worked directly with IRG 1, the group's graduate students interacted with the other CNS Fellows in productive ways. The net effect was to help communicate the value of historical scholarship and deepen the overall engagement at the CNS with methods and tools from science and technology studies.

Overpotential
(Mathew N. Eisler)



VISIONEERS ARE INDISPENSABLE MEMBERS OF A WEB OF RELATIONSHIPS THAT, IN THEIR DIVERSITY, CONSTITUTE AND CO-PRODUCE BOTH SCIENCE AND SOCIETY.

Connecting With Diverse Audiences

Throughout IRG 1's lifespan, its members made a concerted effort to connect their scholarship to a diverse set of audiences. Our motivation was simple – given the considerable resources devoted by the NSF to this collaborative project, it was seen as both necessary as well as professionally responsible to demonstrate the value of humanities scholarship in general and the histories of science and technology specifically to as wide a group of people as possible. The success we had in this effort is borne out by both the number and range of venues in which we presented in our work.

The most obvious audience for our work was naturally our home communities in the history and STS fields. The number of talks, panels, and publications our group was involved with was already noted. Our venues were not chosen randomly. For example, because of our close interactions with scientists and engineers as both historical actors and interview subjects, we consciously placed articles in venues such as *Nature Nanotechnology* and *Physics Today*. On several occasions, we gave talks to groups of scientists. In a similar vein, Slaton's work found traction with people in the STEM and education diversity community. Casting their focus more broadly, IRG 1 members communicated their ideas and findings to a wider audience of business leaders, via venues such as the World Economic Forum and the Center for Equitable Development. Finally, we made efforts to engage with the general public. In 2012, for example, McCray started a blog as an offshoot of his *Visioneers* book. To date, over 75,000 people have visited it. Taken together, IRG 1's belief in creating historical research resulted in writing and talking a "usable past" perceived of value to a diverse set of communities.

The Value of Critical Historical Scholarship

When IRG 1 began, the value of historical research on nanotechnology was decidedly in question. Prominent figures in various government agencies criticized the notion that nanotechnology had any history prior to the early 1990s, while leading figures in the nanoscience community questioned whether the humanities had anything worthwhile to say about nanotechnology. Conversely, leading figures in the history of science and technology were critical of our aims: nanotechnology was, they believed, all hype; it was too recent for "real" history; and any history that could be done would be too internalist and in the service of IRG 1's patrons.

At a superficial level, IRG1's record of honors from our colleagues has demonstrated that historical research on nanotechnology can have value as historical scholarship; we have advanced the state of the art in the history of science and technology. Similarly, our record of publication in the scientific equivalent of mass-circulation periodicals (*Science, Nature, Physics Today, IEEE Spectrum*) shows that there is real desire for accessible history of nanotechnology among practicing scientists and engineers. Finally, profiles of our research in venues such as the World Economic Forum and *New Yorker magazine*, and published by popular presses such as Basic Books, show that our work speaks to wider debates about scientific and technological progress.

So what did we have to say in those wider debates? A decade of research can't be summarized easily, but **three points cover many of the points we have offered to critical thinking about nanotechnology and other "emerging" technologies. First, there's a great deal of nanotechnology that isn't explicitly called "nanotechnology." Most obviously, the semiconductor industry has been a nano industry for more than a decade, and yet has eschewed use of the nanotechnology label. Very little work from the standpoint of Ethical, Legal, Social Implications (ELSI) of emerging technologies has examined the semiconductor industry, despite its political and economic importance and its historical influence over the fields that are arrayed under the nanotechnology umbrella.**

Second, any conversation about the ethical, legal, and social implications of those things that are explicitly labeled as "nanotechnology" should pay attention to the places where that label has made a real difference. Much nano-ELSI work attempts to forecast and prepare for scenarios for a future that has not yet (and probably won't ever) come to pass – as if contemporary nanotechnology has not made a significant difference in the world. And yet, institutions that are labeled as "nanotechnology" have made a difference in some areas – particularly in the reorganization of pedagogy and research in US science and engineering, especially at research universities, for example through the adoption of certain keywords such as "interdisciplinary" and "translational" as synonyms for "good." The use of nanotechnology to reorganize higher education has not been a topic of much critical examination in nano-ELSI. Yet an historical examination of how nanotechnology came to be makes evident the changes that have been wrought in

A HISTORICAL EXAMINATION OF HOW NANOTECHNOLOGY CAME TO BE MAKES EVIDENT THE CHANGES THAT HAVE BEEN WROUGHT IN AMERICA'S RESEARCH UNIVERSITIES – AND COMMUNITY COLLEGES – AND OFFERS GROUNDS FOR A CRITICAL APPRAISAL OF WHETHER THOSE CHANGES HAVE BEEN BENEFICIAL.

America's research universities – and community colleges – and offers grounds for a critical appraisal of whether those changes have been beneficial.

Third, IRG 1 has shown in a variety of ways that any debate about nanotechnology or other emerging technologies must include a very diverse ecology of actors such as futurists and "visioneers" and others who are difficult to accommodate in a policy or ethics or ELSI frame. At times, the NNI has treated nanotechnology's visioneers as distractions or as irrelevant to "real" science and policy; conversely, some nano-ELSI has treated the works of visioneers as isolable objects of study. We have shown, however, that visioneers are indispensable members of a web of relationships that, in their diversity, constitute and co-produce both science and society.

Finally, it should be noted that the work of historians of science and technology departs at times from that of other humanities or social science researchers who study these sectors (say, sociologists and anthropologists) in tracing larger cultural contexts and causalities, and of course, in trying to explain change over time. In other words, a particular technology or scientific priority, in a given historical setting, may shed light on much larger cultural undertakings, such as those associated with industrialization, democratization or globalization. The projects developed by IRG 1 thus demonstrate that the historical study of nanotechnology may well inform practices within nano-focused STEM realms, but also offer analyses applicable to the wider history of American education and labor, and also to a critical history of technical standards and related topics such as maintenance, environmental health, and circulations of scientific knowledge.

Implications for Future STS Scholarship

When historians focus either on very recent events, or treat more distant periods as offering usable lessons for the present, the term "applied history" is sometimes invoked. Distinct from policy analysis or even from that research normally included under the broad rubrics, "Science, Technology and Society" and "Science and Technology Studies," this sort of scholarship incorporates rigorous analysis of longer-term cultural conditions and causalities. It considers issues such as the appropriate demarcation of historical periods, the identification of historical subjects as such, and other analytic problems. For IRG 1 members, such concerns helpfully brought us to the question of whether and how "nanotechnology" represented a historically novel industrial or epistemic enterprise, for example, an inquiry most IRG 1 participants have found to be very suggestive. However, positioning one's research as applied history presents some challenges that one or more IRG 1 researchers encountered.

For one thing, humanistic research on STEM fields, especially if conducted by those without previous training in STEM areas, is sometimes dismissed by observers as superficial or uninformed. This dismissal can be sounded both by those within STEM, and by those in the academy representing other humanistic subject areas (how, we are sometimes asked, can a non-scientist understand science?). Second, disciplinary self-identification in all of the above social science fields is insistent, and there are challenges for historians who wish to project authority as observers of contemporary STEM policy and practice. The value of history to current day nano-sector operations and public welfare is not entirely established for non-

Historical Analogies and the Regulation of Nanotechnology

Research by CNS-UCSB Graduate Fellow Roger Eardley-Pryor; work supervised by Patrick McCray, CNS-UCSB co-PI

MAIN FINDINGS

Comparisons between nanotech and prior technologies are shaped by historically contingent definitions of nanotecnology:

- One's definition of nano determines the appropriate analogy to previous technologies, and thus the particular form of oversight/regulation

Science – including nanoscience – is socially constructed, as is the regulation of science:

- The EU and Canada established a nano definition politically to regulate it and protect human & environmental health
- The US attempt to define nano based only on science forestalls protections for workers, consumers, and the environment

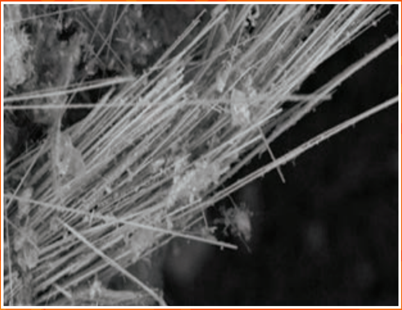
METHODS

Use of Retrospective for Prospective:

- Analysis of analogies between nanotech and prior emerging technologies to suggest future regulation of nanotechnology
- Historical analogy as guide to anticipatory governance framework
- Analogy as form of logic in times of uncertainty; "a device of anticipation"

Analogies to Nano:

- Existential, Invisible Threat: Fallout & DDT
- Specific Material: Asbestos
- Technique for Manipulation: rDNA & GMOs



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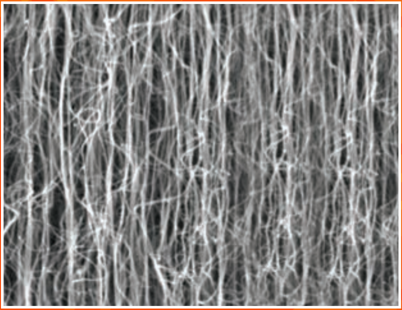


CARBON NANOTUBES

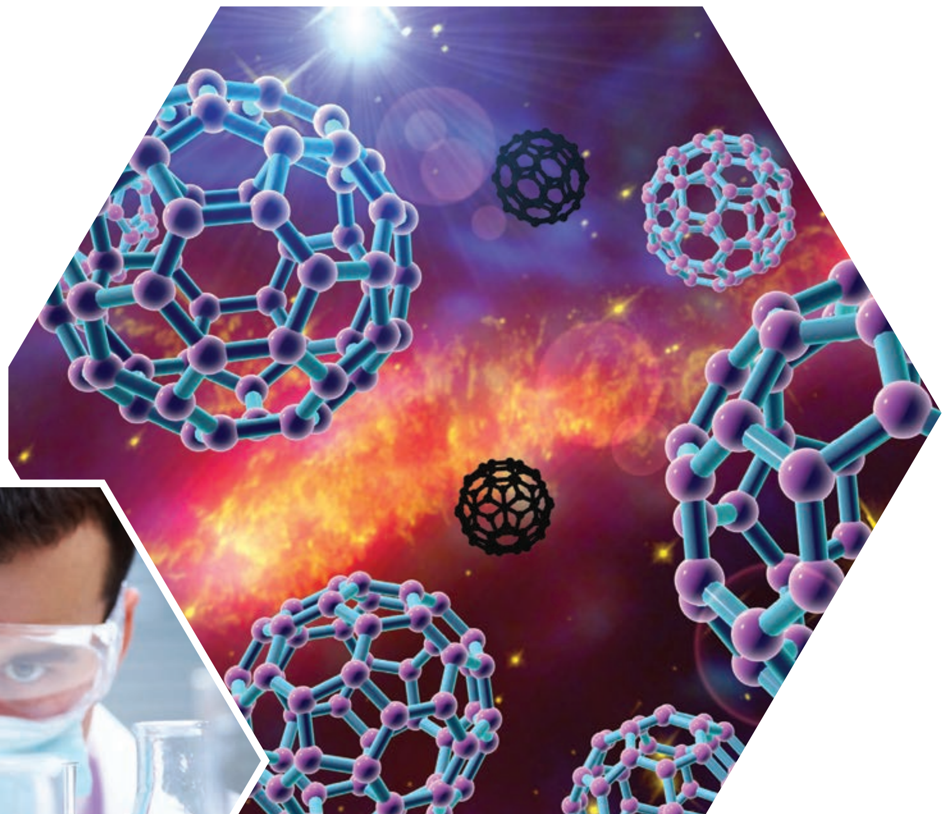
Eardley-Pryor, Roger and Patrick McCray, "Take a Little Risk? Historical Analogies and the Regulation of Nanotechnology." Manuscript in Preparation. Variations of this work were presented at the University of South Carolina, at S.NET in Tempe, AZ, 4S in Cleveland, and the Business History Conference in Philadelphia.

THE VALUE OF HISTORY TO CURRENT DAY NANO-SECTOR OPERATIONS AND PUBLIC WELFARE IS NOT ENTIRELY ESTABLISHED FOR NON-HISTORIANS, AND FOR AT LEAST SOME IRG 1 MEMBERS, THE PROCESS OF DELINEATING HISTORY'S ROLE IN CURRENT STEM PRACTICE IS FELT TO BE AN ONGOING, THOUGH CRUCIAL, CHALLENGE.

historians, and for at least some IRG 1 members, the process of delineating history's role in current STEM practice is felt to be an ongoing, though crucial, challenge.

In addition, there are many sites of STEM practice that welcome humanistic inquiry, but not necessarily with the aim of reflection or self-critique. Historians of nanotechnology and other STEM areas may raise difficult issues regarding economic and environmental sustainability; public participation in scientific or funding decision-making; education; or labor that are seen by our subjects to be misinformed or even undermining. In these cases, an ameliorative function for historians (say, "communicating nanotech advances with the public") is sometime preferred, which of course would be incompatible with critical, open-ended historical research. Vitally, however, we want to acknowledge that the potential of history to offer societally useful perspectives regarding STEM, even where a welcome is extended, is not at all certain. Our institutional positions or global privileges may make critique unlikely, for instance; one aim of IRG 1's collaborative structure was to assure that others' voices informed our own historical analyses. But even here, our shared epistemic priorities may be foreclosing important self-critique. **In short, IRG 1's aims of providing critical, historical perspectives on nanotechnology requires further self-reflection, and we suggest, always will.**

THIS SORT OF SCHOLARSHIP INCORPORATES RIGOROUS ANALYSIS OF LONGER-TERM CULTURAL CONDITIONS AND CAUSALITIES. IT CONSIDERS ISSUES SUCH AS THE APPROPRIATE DEMARCATION OF HISTORICAL PERIODS, THE IDENTIFICATION OF HISTORICAL SUBJECTS AS SUCH, AND OTHER ANALYTIC PROBLEMS.



IRG 1: EXPLORING NANOTECHNOLOGY'S ORIGINS, INSTITUTIONS, AND COMMUNITIES

Key Findings, References, Participant List

Key Policy-Related Findings From Our Research

- Nanotechnology did not emerge ex nihilo as an American research initiative circa 2001. Rather, it was the culmination of years of research and investment – much of it sponsored by federal agencies – that created an extensive suite of available and accessible tools, expertise, and communities.

- Much of today's current nanotechnology infrastructure exhibits what a sociologist would call institutional isomorphism. Centers and research laboratories are built on preexisting models and templates of what has (and hasn't) worked in other areas of research such as materials science. For example, NSF began funding multiple waves of academic centers. One of the first of these, Cornell's National Research and Resource Facility for Submicron Structures, became a crucial driver in the creation of nanotechnology institutions in the '80s and '90s.

- There is very little new knowledge in nanotechnology today – i.e., knowledge that is different from (or would not have been created by) more traditional fields like chemistry, materials science, and electrical engineering. The hope of supporters, though, is that by creating these new institutions now, new forms of knowledge will emerge down the road.

- The complex nature of technological ecosystems translates into a variety of actors essential for successful innovation. One species is the visioneer, a person who blends engineering experience with a transformative vision of the technological future and a willingness to promote this vision to the public and policy makers.

- Although it is often elided in historical accounts and present-day studies of nanotechnology, our research has shown the central importance of the micro/nano electronics industry to the development of nanotechnology as a research enterprise over the last half century. Our work on spintronics – an area of contemporary research that was critical to the further miniaturizing of computer hard drives in the 1990s and which served as the basis for the 2007 Nobel Prize in Physics – demonstrated its transition from a laboratory-based basic science discovery made in 1988 to a field funded by DARPA and other military agencies to one which is supported by university-corporate partnerships. Work such as this enabled us to discover "hidden histories" of nanotechnology and illuminate changing relationships between science/technology and academe/industry.

- Documenting the history of emerging technologies is an exceedingly difficult task. Often there are no formal archives for the historian or STS scholar to turn to. One often-overlooked outcome of IRG-1 work is both uncovering as well as preserving essential historical materials that will be valuable, we imagine, for both future scholars as well as policy makers keen to understand a past research initiative. These include the collection of dozens of oral history interviews as well as the permanent preservation of research materials used by IRG-1. For example, IRG-1 leader McCray donated 17 boxes of collected archival material to Stanford University's Special Collections in 2016.

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* **For a complete cumulative list of IRG 1 publications 2005-2016, please see the IRG 1 section of www.cns.ucsb.edu; a full publication list is also available at the CNS escholarship repository http://escholarship.org/uc/isber_cns**

Participant List

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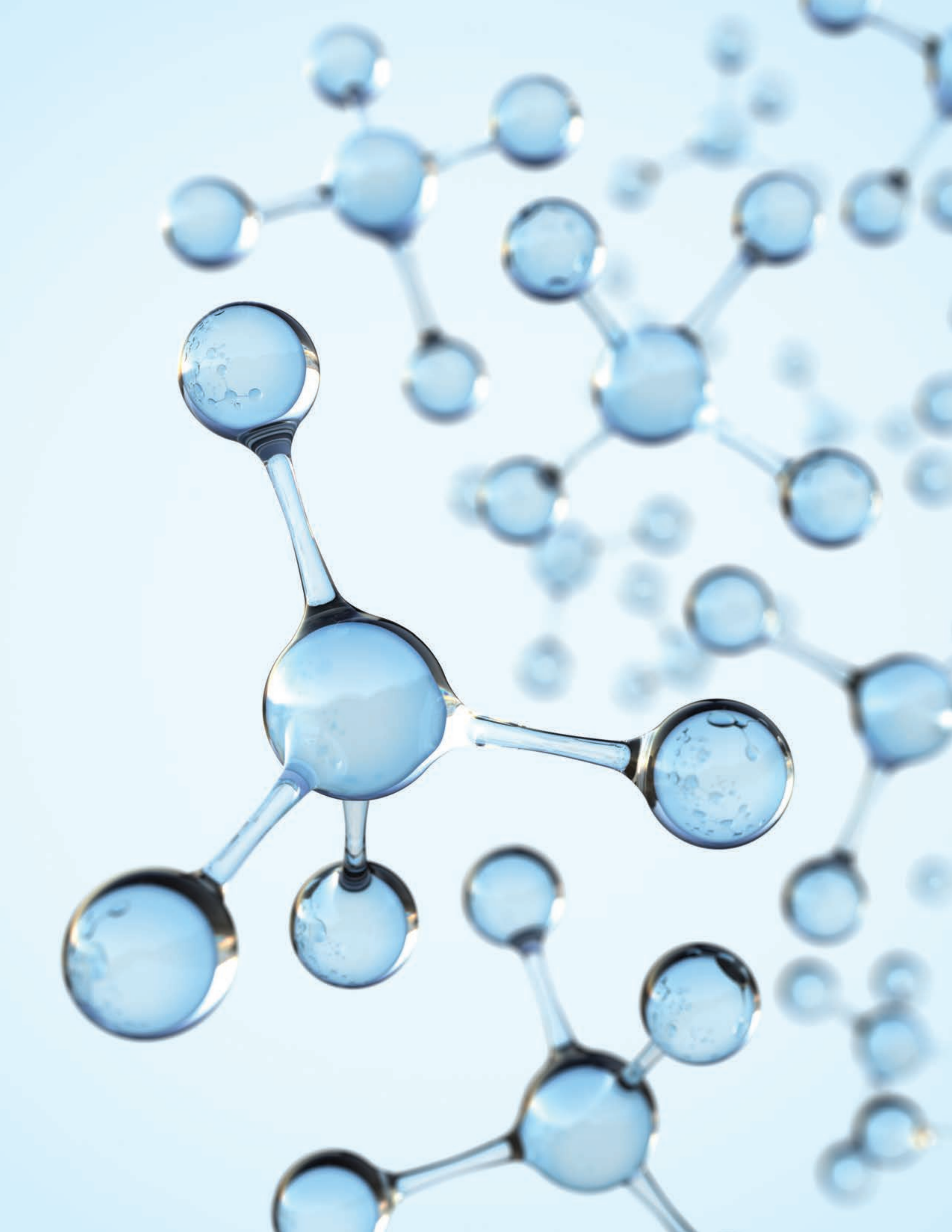

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